SERDP FINAL REPORT: Integrated Climate Change and Threatened Bird Population Modeling to Mitigate Operations Risks on Florida Military Installations

(SERDP – RC1699)

Research Team

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14. ABSTRACT Climate change is expected to significantly alter low-lying coastal and intertidal areas, which provide important seasonal habitat for a variety of shoreline-dependent organisms. This project developed a set of habitat- and species-based models for the coastal Threatened, Endangered, and At-Risk Species (TER-S): Snowy Plover (*Charadrius nivosus*), Piping Plover (*C. melodus*), and Red Knot (*Calidris canutus*). The models were used to predict risk to the TER-S under different climate change scenarios in Eglin and Tyndall Air Force Bases (AFB) and surrounding areas. The model predictions and site use data were utilized in a risk-informed, multi-criteria decision analysis framework to allow systematic evaluation of management options at Eglin and Tyndall. Overall, projected habitat types at Eglin AFB are more stable over time than Tyndall AFB or the whole Gulf Coast of Florida. The Gulf Coast simulations show that the Snowy Plover population size will decline faster than the area of habitat or carrying capacity. MCDA returned variable results in ranking preferred management alternatives because of the uncertainty in the system. Beach nourishment and exclosures were the preferred management alternatives and no action was the least preferred. The integrated modeling and management framework developed in this study can be generalized to other coastal facilities and environmental management needs.

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Sea-level rise, Land-cover, Habitat suitability, Metapopulation Rise, Snowy Plover, Florida, Gulf of Mexico, Decisions, Alternatives, Stakeholders, Climate Change

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Land-cover
Habitat suitability
Metapopulation Rise
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Climate change

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List of Acronyms

AFB: Air force base
C-CAP-NOAA: Coastal Change Analysis Program data from the National Oceanic and Atmospheric Administration
DoD: Department of Defense
ERDC: Engineer Research and Development Center
ESTCP: Environmental Security Technology Certification Program
FSU: Florida State University
FWC: Fish and Wildlife Conservation
GIS: Geographic information system
GSA/UA: Global sensitivity and uncertainty analysis
IPCC: International Panel on Climate Change
IUCN: International Union for Conservation of Nature
MAVT: Multi-attribute value theory model
MaxEnt: Maximum Entropy
MCDA: Multi-criteria Decision analysis
NED: National elevation dataset
NOAA: National Oceanographic and Atmospheric Administration
NPS: National Park Service
OAT: One-parameter-at-a-time
RA: Risk assessment
SERDP: Strategic Environmental Research and Development Program
SEV: Socio-ecological value
SLAMM: Sea Level Affecting Marshes Model
SLR: Sea level rise
SMAA: Stochastic Multi-criteria Acceptability Analysis
SP: Snowy Plover
SRI: Santa Rosa Island
TER-S: Threatened, endangered, and sensitive species
UF: University of Florida

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Abstract

Objective

Climate change (via sea-level rise and changing weather patterns) is expected to significantly alter low-lying coastal and intertidal areas, which provide important seasonal habitat for a variety of shoreline-dependent organisms. Many coastal military installations in Florida have coastal habitats with shoreline-dependent bird data that strongly illustrates their seasonal importance for birds.

Our objectives were to: (1) assess current vulnerability scenarios and information on selected Florida military installations, (2) develop a set of habitat- and species-based models for the coastal Threatened, Endangered, and At-Risk Species (TER-S) Snowy Plover (*Charadrius nivosus*), Piping Plover (*C. melodus*), and Red Knot (*Calidris canutus*), (3) assess the current prediction level and assumptions of selected categories of TER-S models for use in benchmarking model performance and uncertainty levels, and (4) integrate the scientific data, modeling and uncertainty results into a risk-informed, multi-criteria decision analysis system to allow systematic analysis of potential management options.

Technical Approach

The technical approach utilized the Sea Level Affecting Marshes Model (SLAMM), MaxEnt species distribution model, and RAMAS-GIS metapopulation model to explore current and future habitat/spatial distribution/population states, as well as the spatial and temporal patterns of these uncertain results with global sensitivity and uncertainty analysis. Joint simulations of sea level rise at 0.2, 0.5, 1.0, 1.5 and 2.0 meters were conducted at 30 m horizontal grid resolution for the Eglin Air Force Base/Santa Rosa Island areas and for the entire Florida Gulf Coast (Pensacola to Naples) at 120 m grid resolution. Multi-criteria decision analysis (MCDA) was then used to rank alternative management solutions under potential future scenarios. The results from JSMAA and Logical Decisions software were compared. To trade-off military and ecological needs of TER-S, we developed a spatial portfolio decision model for the selection of the optimal set of restoration alternatives in space and in time. This optimal portfolio set maximizes the balance between the habitat which support TER-S (natural resources needs), land requirements for training (military needs) and restoration costs.

Results

Although uncertainty levels are high, consistent simulation results show key results in two areas: potential habitat losses and Snowy Plover population dynamics. Overall, projected habitat types at Eglin AFB are more stable over time than Tyndall AFB or the whole Gulf Coast of Florida, manifesting the least changes between 2010 and 2100 at sea-level rise (SLR) = 2.0 m in all land cover categories except tidal flats. The Gulf Coast simulations show that the Snowy Plover population size will decline faster than the area of habitat or carrying capacity, demonstrating the necessity of incorporating population dynamics when assessing the impacts of SLR on coastal species, particularly the resident Snowy Plover, wintering Piping Plover, and the migratory Red Knot. MCDA returned variable results in ranking preferred management alternatives because of the uncertainty in the system. Beach nourishment and exclosures were the preferred management tools and no action was the least preferred. MCDA also showed that a better understanding of species reproductive strategies will provide a more definitive alternative ranking.

Benefits

The benefits of this research were: (1) integration of models that are generally applicable to any coastal ecosystem; (2) quantification of the drivers and uncertainty of ecogeomorphological processes; and (3) formulation of environmental management recommendations for the sustainability of Florida coastal ecosystems.

1. Objective

The overall objective of this research was to integrate multi-scale climate, land use, and ecosystem information into a systematic toolset to explore climate change and sea level rise (SLR) effects on habitat and population dynamics for Snowy Plover (*Charadrius nivosus*) and simplified habitat effects on Piping Plover (*Charadrius melodus*), and Red Knot (*Calidris canutus*) on the Florida Gulf Coast including Eglin Air Force Base, Tyndall Air Force Base (AFB), and Pensacola Naval Air Station. Note that direct response of species to global climate change, such as adaptation or migration, are not within the scope of this modeling effort. Species response to climate represents are future area of research that adds to the utility of the products resulting from this effort. This multi-disciplinary research effort integrated three primary component areas: (A) multi-scale climate data including historical and projected conditions, (B) quantitative SLR tools, including habitat suitability models, meta-population models, global sensitivity/uncertainty analysis methods as well as multi-criteria decision analysis, and (C) the practical, management/conservation activities that might be affected by the information generated by the coupled climate data/population/decision models.

This advanced modeling integration project responds to the SERDP Statement of Need (SON) in the following points *(each original SON is listed in italics)*:

1. Predictions of how coastal ecosystems may be altered under potential climate change scenarios for the region.
2. Predictions of the impacts to threatened, endangered, and at-risk species (TER-S) and their habitats of relevance to the Department of Defense (DoD) under potential climate change.
3. Development of predictive models for community disassembly/reassembly processes under potential climate change scenarios and how such processes and the barriers to species movement will affect the ability of TER-S to disperse or migrate.
4. Identification of sentinel species, including TER-S, whose responses to changing environmental conditions can be used as leading indicators of impaired coastal ecosystem function.
5. Development of adaptive management approaches that can mitigate the adverse ecological effects of currently altered habitats and potential climate change scenario impacts.

The overall goal of our research was to provide site-specific information that will be useful to military natural resource managers for identifying the significance of military lands in contributing to the long-term sustainability of TER-S under various climate change scenarios. This goal was executed by MCDA and portfolio decision analysis techniques that integrated data and models of different species and the military capability for providing management solutions at a variety of spatial and temporal scales.

To test this goal, we completed four principle objectives:

1. Assessed current vulnerability scenarios and information on selected Florida installations by documenting and reviewing Florida-specific climate and land use databases and information,

2. Developed a set of habitat- and species-based models for selected coastal TER-S (specifically Snowy Plover for species effects and Piping Plover and Red Knot for habitat effects)
3. Assessed the current prediction level and assumptions of selected categories of TER-S models for use in benchmarking model performance and uncertainty levels
4. Integrated the scientific data, modeling and uncertainty results into a risk-informed, multi-criteria decision analysis (MCDA) system to allow systematic analysis of potential management options.

2. Background

Climate change (via sea-level rise and altered weather patterns) is expected to significantly alter low-lying coastal and intertidal areas, which provide important seasonal habitats for a variety of shoreline-dependent organisms. Figure 4 shows a conceptual model of the various forces affecting TER-S on coastal military bases. The general location of the bases are shown in Figure 1. A variety of forces such as climate, land development, and military base management (represented by their information and data) have influence upon TER-S populations and their associated habitats. All these factors have varying levels of uncertainty and variation in their representation as well as their actual influence upon the TER-S. The models that are created to simulate these populations add an additional level of uncertainty to the predicted scenarios that managers request. As a result, two situations tend to arise from most modeling studies; (1) multiple and highly uncertain predictions may be less useful to decision-makers than they expect so they are often disregarded in favor of a more subjective approach or (2) a small sub-set of the predictions may be selected because they are generally acceptable in terms of integration with other information. In both cases, information is often disregarded in the move towards a practical management decision.

Incorporation of these uncertainty issues within adaptive management challenges demands an organized and methodical toolset that can help to parse through the often disparate and complex data that are integrated within an adaptive management framework. Figure 5 shows the advantages in utilizing additional tools focused on uncertainty and decision integration. Recently developed tools include global sensitivity/uncertainty analysis methods (Saltelli et al., 2004; Muñoz-Carpena et al., 2007) and integration/decision analysis tools (Linkov et al., 2004; Kiker et al., 2005; Kiker et al., 2008). The authors suggested that these additional tools can help to answer both technical model/data questions as well as the functional management questions listed in the upper right corner of Figure 5. For example, addressing the question “How does our species and the habitat react under various climate/management scenarios?” Aiello-Lammens et al. (2011) showed that SLR will cause a decline in suitable habitat and carrying capacity for the Snowy Plover. Additionally, the population size is predicted to decline faster than the area of habitat or carrying capacity. When addressing the question “What TER-S policies are worth pursuing?” the MCDA results showed that each of the management alternatives considered (i.e. No Action, Beach Nourishment, Exclosures, and Predator Management) have benefits worthy of investigation. In the following section we introduce the location of study, bird species and model development background.

2.1 Location of Research

Many coastal military installations in Florida have significant coastal habitats with shoreline-dependent bird data, which strongly illustrate their seasonal importance for birds. Recent projections of habitat loss for shoreline-dependent birds at important coastal sites in the U.S. range between 20 and 70% loss (Galbraith et al. 2002). This is particularly worrisome for shoreline-dependent species such as the federally listed Piping Plover (*Charadrius melodus*), Florida state-listed Snowy Plover (*Charadrius nivosus*), and Red Knot (*Calidris canutus*) (likely to soon be Federally listed) that are experiencing significant habitat loss and increasing human disturbance in breeding/nesting, brood-rearing, wintering, and migratory-stopover areas (Guilfoyle et al., 2006). The Florida Fish and Wildlife Conservation Commission (FWC) lists Snowy Plovers as threatened and the US Shorebird Conservation Plan lists them as Extremely High Priority for conservation (Brown et al. 2001). In addition to Snowy Plovers, federally

listed Piping Plovers occur in high numbers (relative to the rest of their non-breeding range) on Florida's barrier islands during the non-breeding season. Piping Plovers are listed by the USFWS as three separate sub-populations: the Great Plains and Atlantic Coast populations are listed as threatened and the Great Lakes population is listed as endangered (USFWS 1996, USFWS 2003). Color-banded individuals from all three populations have been observed during fall migration and winter in Florida (Stucker and Cuthbert 2006; USFWS, Panama City field office, unpublished data). Red Knot populations have declined dramatically during the past decade and there is high potential for this species to be federally listed in the near future. As coastlines move inland as a result of SLR, much of the coastal shoreline will become "water against seawalls" with little or no beach, dune, and intertidal habitats critical to shoreline-dependent bird ecology. Shoreline-dependent organisms will increasingly rely on habitats provided on federal lands where beaches will be able to slowly migrate inland with little constraint.

Figure 1. Region of study.

Considering the effects of climate on natural resources is an issue of significant global concern, and at the national level Florida has been identified as one of the states to be most vulnerable to climatic impacts (U.S. Congress, 1993; National Assessment Synthesis Team, 2001). Coastal military installations in the southeastern United States, such as Eglin AFB, Tyndall AFB, Naval Air Station Pensacola, Cape Canaveral Air Force Station, Patrick AFB, and Marine Corps Base Camp Lejeune, all have significant coastal habitats and shoreline-dependent bird data to suggest their seasonal importance for birds. Recent work by American Bird Conservancy clearly shows the importance of DoD and National Park Service (NPS) lands for breeding Snowy Plovers and wintering Piping Plovers (Figure 3). Eglin AFB and Tyndall AFB, along with State Park and NPS shorelines accounted for the land in which 80% of all estimated nesting Snowy Plover pairs were found in the Florida Panhandle during recent statewide surveys. Tyndall AFB had the highest counts for wintering Snowy Plovers of anywhere in the state (Figure 3) (Lott 2008). There is also a significant need to ensure that coastal areas remain intact

and viable for military training purposes (e.g., amphibious landings). Recent DoD-focused TER-S research and management objectives have stressed the need for greater systems understanding and tool development at a variety of spatial and temporal scales (SERDP/ESTCP/DOD, 2007). Potential land use changes and human population increases, coupled with uncertain predictions for SLR, storm frequency, and intensity have created a significant planning challenge for natural resource managers.

Figure 4 shows a conceptual model of the various forces affecting TER-S on Florida bases. A variety of forces such as climate, land development, and military base management (represented by their information and data) have influence upon TER-S populations and their associated habitats. All these factors have varying levels of uncertainty and variation in their representation as well as their actual influence upon the TER-S. The models that are created to simulate these populations add an additional level of uncertainty to the predicted scenarios that managers request. As a result, two situations tend to arise from most modeling studies; (1) multiple and highly uncertain predictions may be less useful to decision-makers than they expect so they are often disregarded in favor of a more subjective approach or (2) a small sub-set of the predictions may be selected because they are generally acceptable in terms of integration with other information. In both cases, information is often disregarded in the move towards a practical management decision.

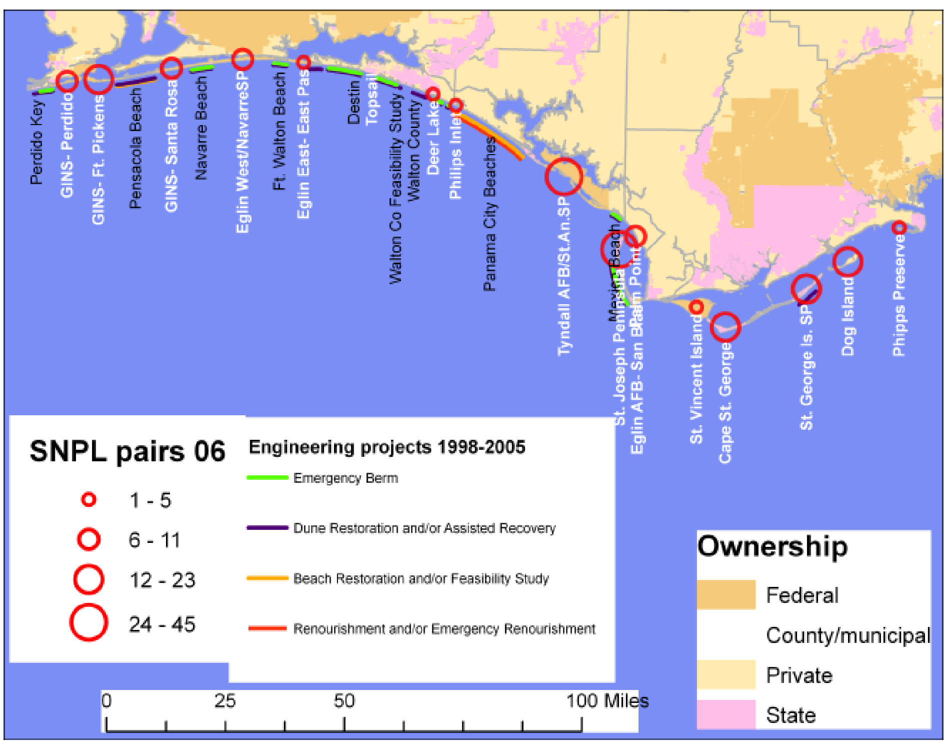


Figure 2. 2006 Snowy Plover breeding pair estimates and sand placement projects from 1998 to 2005 in the Florida Panhandle (data from the FWC) (from Lott 2008).

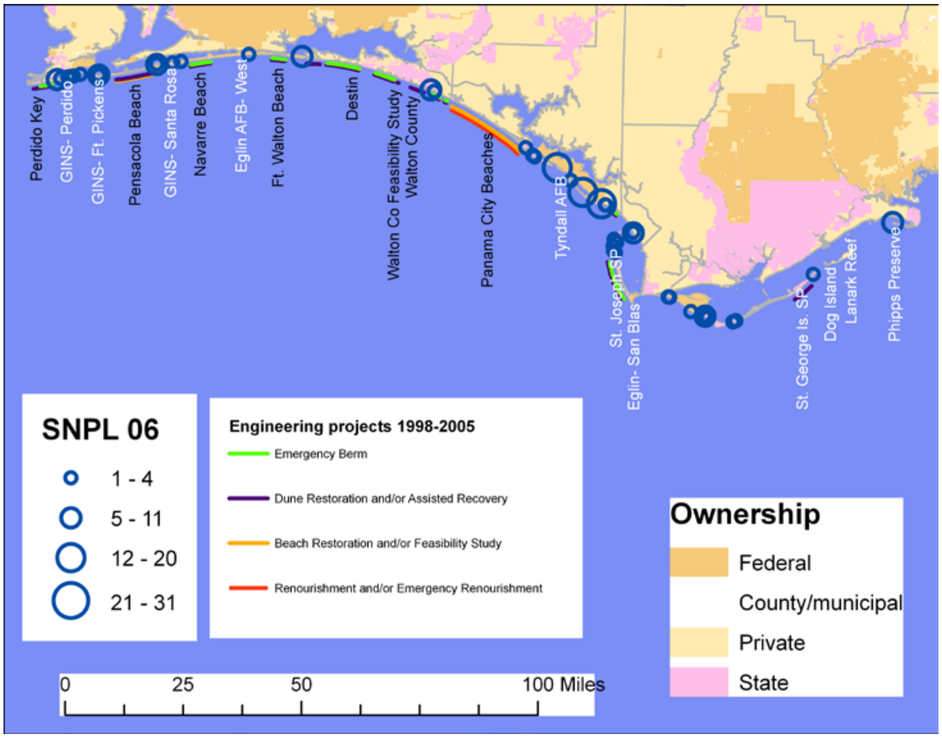


Figure 3. 2006 Distribution of wintering Snowy Plovers and sand placement projects from 1998 to 2005 in the Florida Panhandle (from Lott 2008).

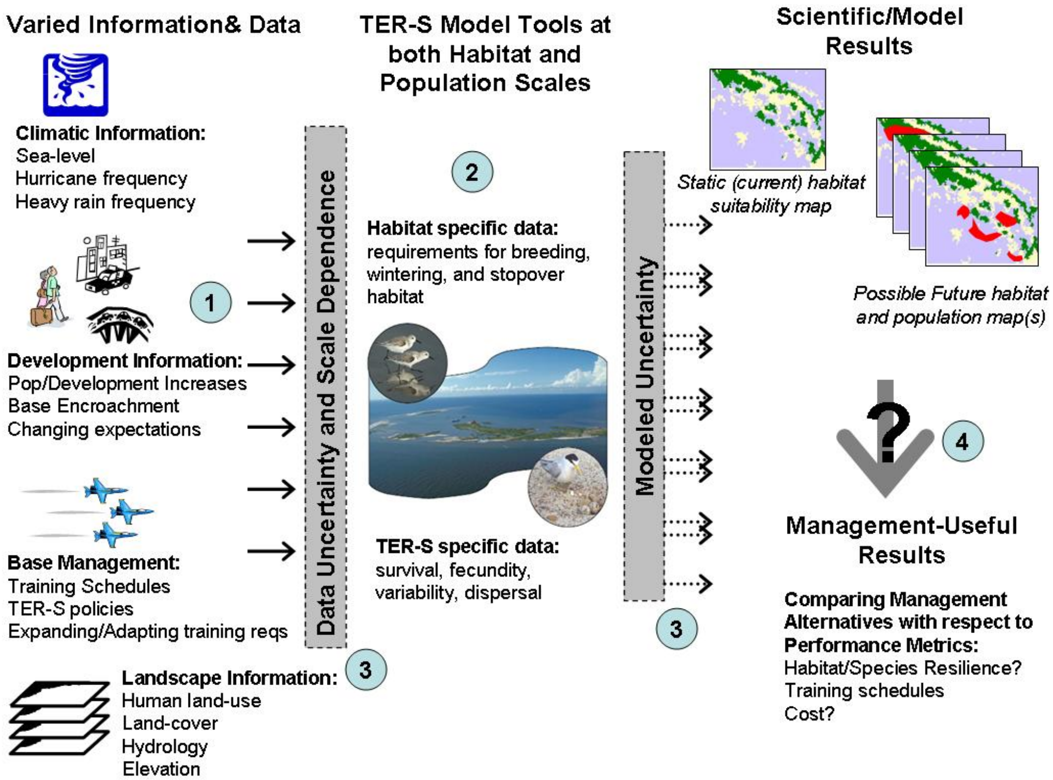


Figure 4. Conceptual model of the interaction showing the relationship of varied and uncertain input information being fed into habitat- and species-focused TER-S models for creation of research products with an uncertain linkage to site-based management-related issues. The circled numbers correspond directly with listed research objectives.

2.2 Toolset Development

Incorporation of these uncertainty issues within adaptive management challenges demands an organized and methodical toolset that can help to parse through the often disparate and complex data that are integrated within an adaptive management framework. Figure 5 shows the advantages in utilizing additional tools focused on uncertainty and decision integration. Recently developed tools include global sensitivity/uncertainty analysis methods (Saltelli et al., 2004; Muñoz-Carpena et al., 2007) and integration/decision analysis tools (Linkov et al., 2004; Kiker et al., 2005; Kiker et al., 2008). The authors suggested that these additional tools can help to answer both technical model/data questions as well as the functional management questions listed in the upper right corner of Figure 5. For example, addressing the question "How does our species and the habitat react under various climate/management scenarios?" Aiello-Lammens et al. (2011) showed that SLR will cause a decline in suitable habitat and carrying capacity for the Snowy Plover. Additionally, the population size is

predicted to decline faster than the area of habitat or carrying capacity. When addressing the question "What TER-S policies are worth pursuing?" the MCDA results showed that each of the management alternatives considered (i.e. No Action, Beach Nourishment, Exclosures, and Predator Management) have benefits worthy of investigation.

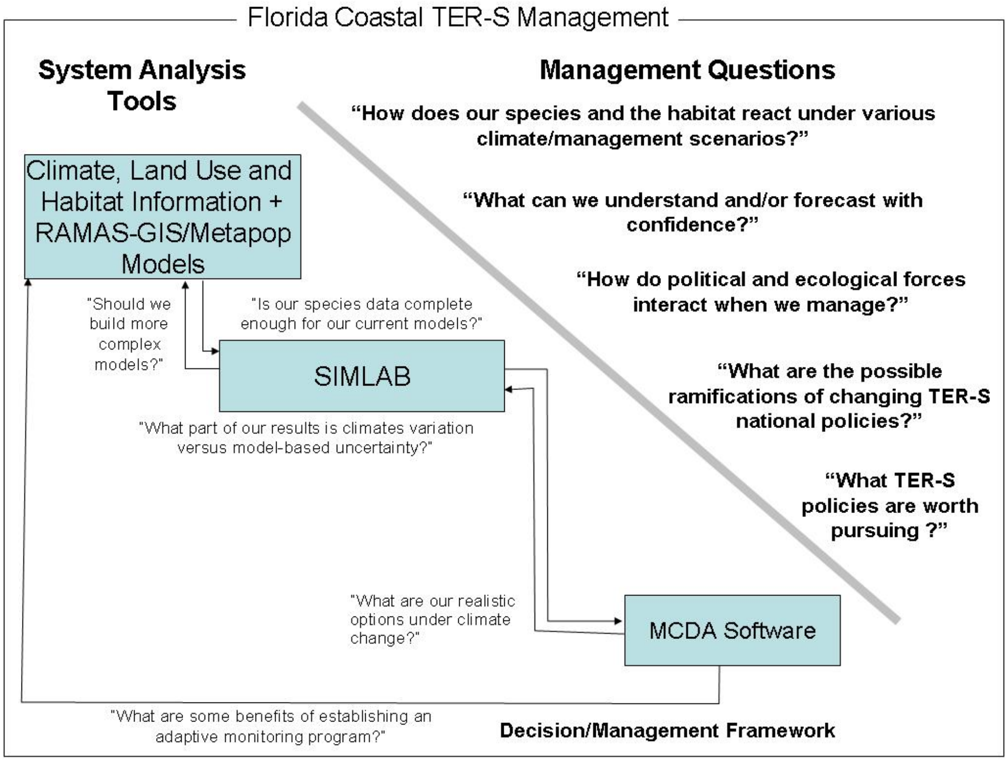


Figure 5. System Analysis Tools and Management Questions.

2.3 Species of Concern

The Snowy Plover (*Charadrius nivosus*) (Figure 6) is a ground nesting shorebird that breeds and winters primarily on unvegetated to sparsely vegetated coastal beaches (and for some inland populations, along shores of alkaline lakes). This species is often described as small (15–17 cm long, 34–58 g) relative to other plovers, with a distinctive white hind-neck collar and a breast band always restricted to lateral patches. Other distinguishing characteristics include pale brown upperparts and dark gray to blackish legs. During the breeding season, male can be distinguished from females by their black crown, ear covert, and foreneck patches. Males and females are mostly indistinguishable during the non-breeding season. Significant coastal development, as well as human recreation along coasts, has contributed to the imperiled status of most Snowy Plover populations. The Pacific coast population is listed by the U.S. Fish and Wildlife Service as threatened and the Gulf coast population is state-listed as endangered in Mississippi and threatened in Florida. The Snowy Plover both breeds and winters in Florida, but little is known about the migratory habitats of this species (Page et al. 2009).

Figure 6. Snowy Plover (Source: http://www.fws.gov/willapa/wildlife/wildlife.html)

The Piping Plover (*Charadrius melodus*) (Figure 7) is a shorebird similar in appearance to Snowy Plover; however, it is slightly larger (17-18 cm long), and has a thicker, shorter bill, orange legs, and in flight reveals a complete white band across upper-tail coverts. The Piping Plover is federally listed throughout its range in the United States. It breeds primarily on alkali flats and sandflats in the Great Plains and Great Lakes, and on beaches along the Atlantic Coast from North Carolina to eastern Canada. During fall, most individuals migrate south to wintering grounds on coastal beaches, sandflats, and mudflats primarily from the Carolinas to Yucatan. In Florida, Piping Plover can be found sparsely distributed along the Gulf Coast during winter, foraging in intertidal areas and along the wrack line (Elliott-Smith and Haig 2004).

Figure 7. Piping Plover (Source: http://www.fws.gov/southdakotafieldoffice/PLOVER.HTM)

The Red Knot (*Calidris canutus*) (Figure 8) is a shorebird larger than both plovers (23–25 cm, ~135 g) that breeds mainly in the Holarctic region at extreme northerly latitudes. During the breeding season, it exhibits bright reddish plumage (often characterized as salmon or reddish-brick), but changes to dull gray during the non-breeding season. Red knots are known for their incredible long-distance migrations, some up to 15,000 km one-way. Many Red Knots migrate and stopover along both coasts of Florida enroute to wintering grounds. Some overwinter in

portions of southern Florida. Primary habitats during the non-breeding season include intertidal, marine habitats, often near coastal inlets, estuaries, and bays (Harrington 2001). In 2007, the USFWS determined that the Red Knot warranted federal protection under the Endangered Species Act, but this action was precluded by higher priority listing actions for species at greater risk.

Figure 8. Red Knot (Source: http://www.fws.gov/northeast/redknot/)

2.4 Sea level rise and habitat simulations

SLAMM (Sea Level Affecting Marshes Model; Warren Pinnacle Consulting, Inc.) was used to simulate the land cover changes of Eglin AFB and the Florida Gulf Coast under different SLR projections. SLAMM divides the whole domain into independent cells, assigning different land cover or wetland categories to each cell. Each wetland type is associated with certain elevation boundaries and conditions (e.g., salinity and proximity to open water) required for that specific wetland type to exist. SLAMM works by continuously accounting for the minimum elevation of the cells as sea levels rise determining whether the cells will remain in their original category or be converted to another land cover. Conversion of a cell to another wetland type is generally governed by the minimum elevation of that cell which is given as follows:

$$ME_t = ME_{t-1} + \Delta t(AR) - SLR_t + X_t \qquad (1)$$

Where *ME* is the minimum cell elevation, *AR* is the site-specific accretion and/or sedimentation rate, *SLR* is the sea level rise, and *t* is the time. To clarify definitions futher, *accretion* refers to the increase in biomass (organic matter deposition and vegetation growth) on marshes due to inundation (Clough, 2010; p17-25). *Sedimentation* on the other hand, refers to the deposition of eroded and weathered sediments on the beach and tidal flat. In this project, we define *beach nourishment* as the further, human-initiated, addition of sediments upon the beach area to mitigate adverse effects of both normal and exceptional coastal erosion events. To incorporate this coastal management element, the SLAMM model was further modified to allow each grid cell to have an additional elevation addition or subtraction from a user specified map and time (represented in equation 1 with X_t). With this model addition, beach nourishment events (increasing cell elevation) or extreme erosion events associated with severe/rare storms (reducing cell elevation) can be simulated as . Sea level rise is estimated at each time step as:

$$SLR_t = GSLR_t + (t_n - t_o)\ (risetrend_{local} - risetrend_{global}) \tag{2}$$

where *GSLR* is the global average sea level rise predicted based on particular growth scenarios, t_n is the current model year, t_0 is the initial year, $risetrend_{local}$ is the local historic trend of sea level rise, and $risetrend_{global}$ is the global historic trend of sea level rise.

In general, the fate of the wetland is determined by the *ME* of the cell compared to the elevation boundaries of the wetland category it belonged to. If the *ME* of the cell is lower than the lower boundary of that wetland category, a fraction of that cell will be converted to another wetland category of lower elevation. This process is referred to as inundation in SLAMM. The fraction of the cell lost (i.e. converted to another wetland class) is computed as follows:

$$FL_t = \frac{\left(\dfrac{LB - ME_t}{\tan\alpha}\right)}{W} \tag{3}$$

where FL_t is the fraction of wetland in the cell lost at time *t*, *LB* is the lower boundary of the wetland category, α is the slope of the cell, and *W* is the width of the cell. For cells adjacent to the water, additional fractions may be lost due to erosion if the erosion threshold set by the model is exceeded. Additional cell fraction lost, FL_E, due to erosion is given as:

$$FL_{E,t} = \Delta t\left(\frac{ER}{W}\right) \tag{4}$$

where *ER* is the site-specific erosion rate specified by the user.

Input data in SLAMM consist of the elevation, slope, land cover, site-specific information (e.g., erosion rate, accretion rate, storm frequency), and SLR scenarios. Output from SLAMM is a simulated land cover through time.

SLAMM simulates local mean SLR using the International Panel on Climate Change (IPCC) scenarios, which were based on IPCC 2007 Climate Change report (Meehl et al., 2007). Although the different IPCC scenarios are coded directly into SLAMM, the model also allows users to specify their own local mean SLR by 2100. It then scales this value using the A1B scenario to determine the local mean SLR in every time step. Considering the range of SLR values from different projections, land cover was simulated in SLAMM on a yearly time step at SLR equal to 0.2, 0.5, 1.0, 1.5, and 2.0 m by 2100.

2.5 The role of uncertainty in TER-S model development

An important motivation of any model development and multi-scale simulation is the assumption that the information derived from these tools will allow managers and decision-makers to both better comprehend system dynamics as well as craft meaningful or appropriate solutions to adverse potential conditions. Integrated climate and ecological models are often complex and require a large number of inputs. Such mathematical models are built in the presence of uncertainties of various types (input variability, model calibration data, and scale). In addition, there is a growing interest in evaluating the contribution of model structural uncertainty (*i.e.*, from model algorithms and design) to the overall uncertainty of the model outputs (Draper, 1995; Beven, 1993; Beven and Binley, 1992). The role of *uncertainty analysis* is to propagate all these uncertainties onto a model output, while *sensitivity analysis* is used to determine the

strength of the relation between a given uncertain input and a model output. Thus sensitivity analysis identifies the key contributors to uncertainties, while uncertainty analysis quantifies the overall uncertainty, so that together they contribute to a reliability assessment of the model (Scott, 1996). If model uncertainty is not evaluated formally, the science and value of the model will be undermined (Beven, 2006). The issue of uncertainty of model outputs has implications for policy, regulation, and management, but the source and magnitude of uncertainty and its effect on ecological assessment has not been studied comprehensively (Beven, 2006; Muñoz-Carpena et al., 2006; Shirmohammadi et al., 2006). Reckhow (1994) proposed that although uncertainty assessment can improve risk assessment and decision-making, it does not eliminate uncertainty nor change the fact that, because of uncertainty, some decisions will have consequences other than those anticipated. Rather, the explicit integration of uncertainty in modeling studies should improve environmental management and decision-making.

Input factors of interest in the sensitivity analysis are those that are uncertain; that is, their value lies within a finite interval of non-zero width. The sensitivity and related uncertainty of a model output to a given input factor has been traditionally expressed mathematically in terms of the derivative of the model output with respect to the input variation, sometimes normalized by either the central values where the derivative is calculated or by the standard deviations of the input and output values (Haan et al., 1995). These sensitivity measurements are "local" because they are fixed to a point (base value) or narrow range where the derivative is taken. These local sensitivity indexes are classified as "one-parameter-at-a-time" (OAT) methods, *i.e.*, they quantify the effect of a single parameter by assuming all others are fixed (Saltelli et al., 2005). Local OAT sensitivity indices are only efficient if all factors in a model produce linear output responses, or if some type of average can be used over the parametric space. Often, the model outputs' responses to changes in the input factors are non-linear, and an alternative "global" sensitivity approach, where the entire parametric space of the model is explored simultaneously for all input factors, is needed. The advantage of the global approach over a local OAT method is that it results in the ranking of parameter importance and provides information not only about the direct (first order) effect of the individual factors over the output, but also about their interaction of higher order effects.

As an alternative to the techniques outlined above, sometimes a crude variational approach is selected in which, instead of a derivative, incremental ratios are taken by moving factors one at a time from the base line by a fixed amount (for example, 5 percent) without prior knowledge of the factor uncertainty range. Traditional sensitivity analysis methods are limited since they only explore a prescribed (and usually small) parametric range, and can only efficiently consider a few inputs since they are based on OAT approaches (Saltelli et al., 2005).

When the model output response is non-linear and non-additive, as with most complex ecological model outputs, the derivative techniques are not appropriate and global techniques that evaluate the input factors of the model concurrently over the whole parametric space (described by probability distribution functions) must be used. Different types of global sensitivity methods can be selected based on the objective of the analysis (Cacuci, 2003; Saltelli et al., 2000, 2004). This study proposes a model evaluation framework (Muñoz-Carpena et al., 2007) around two such modern global techniques, a screening method (Morris, 1991) and a quantitative variance-based method (Sobol', 1993). The screening method allows an initial reduction in the number of parameters to use in the Fourier Amplitude Sensitivity Test (FAST) analyses. The FAST method is a quantitative variance based global sensitivity and uncertainty analysis technique. Its high computational cost requires the reduction of inputs using the

screening method. The proper use of global sensitivity methods can yield four main products for this application: (1) assurance on the model's behavior (absence of errors), (2) ranking of importance of the parameters for different outputs, (3) effect of changing modeling structure, and (4) type of influence of the important parameters (first order or interactions) (Saltelli, 2004). In addition, based on the outputs derived from this analysis, a complete uncertainty assessment of the model application can be obtained and used as the basis for the risk-informed decision analysis of proposed management scenarios for the region.

Incorporation of these uncertainty issues within adaptive, ecosystem management challenges such as climate change and TER-S demands an organized and methodical toolset that can help to parse through the often disparate and complex data that are integrated within an adaptive management framework. Recently developed tools that can be successfully integrated into a scientifically defensible and decision-useful suite of method and tools include habitat-based metapopulation models with dynamic spatial structure (Akçakaya et al., 2003, 2004, 2005) for estimating species viability under future habitat changes, global sensitivity/uncertainty analysis methods (Saltelli et al., 2004; Muñoz-Carpena et al., 2007; Jawitz et al., 2007) and integration/decision analysis tools (Kiker et al., 2005; Kiker et al., 2006; Linkov et al., 2006, Bridges et al., 2008).

The primary advantage of an integrated approach is not to seek more ecosystem data or to build ever-expanding models, which is a common pitfall of adaptive management implementation. Instead, these tools provide a set of systematic methods *to assess and plan for what level of information and model representation are necessary to match current system understanding with management objectives*. Climate change and ecosystem issues are inherently challenging and require greater amounts of coordination, consensus and complementarities among people, their management processes and their systems analysis tools. An important aspect of our research is a comprehensive analysis of sensitivity and uncertainties that result from measurement errors, inadequate understanding of natural and human processes and their interactions, and, especially in the case of climate change, from unpredictability of the society's response to the threat of global warming. Accordingly, a statistical framework was used following that described by Muñoz-Carpena and others (2007) to evaluate the global sensitivity and uncertainty of model predictions (shorebirds populations) to fluctuations in food supplies, and climate-related variables such as sea-level and frequency of hurricanes and other extreme events.

2.6 Risk-based multi-criteria decision analysis

As with many environmental management applications, developing a framework for selecting appropriate management alternatives and making abatement and restoration decisions with uncertainty and incomplete information is the current challenge for the field of environmental management. Multi-criteria Decision Analysis (MCDA) coupled with Risk Assessment (RA) is useful for integrating heterogeneous scientific information (e.g., monitoring data, modeling, risk assessment), as well as for explicitly incorporating technical personnel' and stakeholders' value judgments in deciding on the best course of action. MCDA represents a collection of approaches for structuring the decision-making process to organize the information provided by site-specific sampling and climate change modeling and the information resulting from decision maker intuition, environmental factors and situation criticality (Linkov et al., 2006). Environmental data are used to develop a weighting structure for the set of metrics that reflects military priorities and interests. Utility theory is a type of MCDA that is used here to integrate information into a score for each of the alternative action plans being evaluated within

the analysis. Strengths of Utility Theory include the ease of comparison between alternatives and the fact that a choice of a preferred alternative can be transparent. Weaknesses of Utility Theory include the applicability of the utility to decision makers and the subjective weighting of criteria (Linkov et al., 2006). MCDA offers the structure and quantitative approaches that can be used together as an exploratory tool for considering the full range of issues germane to a problem/solution in a systematic, rational, and efficient manner.

3. Materials and Methods

This section highlights the research methodologies and literature for each of the different research elements including databases, models, sensitivity/uncertainty analysis techniques and decision analysis tools. Many of our methodologies have been documented in peer review literature, either in previous studies or in our own research results. These are documented in the text and listed in the reference section.

3.1 Preparation and analysis of climate, topographical and ecological data

Environmental data including topological data (120m, 30m and 1-5m scales) were reviewed for application into species distribution models (i.e. MaxEnt), the SLAMM model and the RAMAS metapopulation model. After team meetings considering various model requirements and domains, the GIS/simulation domain was expanded to include the entire Florida Gulf Coast for modeling population level effects. We received hourly interpolated tracks/intensity of North Atlantic tropical cyclones from the SERDP-funded project at Florida State University (SI-1700). Two jointly-authored UF/FSU/ERDC publications using these data (Convertino et al., 2011b, d) have been published. Additionally, Lidar and NED data were analyzed for spatial and temporal coverage of near shore areas for use in a more detailed habitat model and SLAMM simulations. In addition, team members (Dr. Fischer) coordinated ongoing research by Boise State University and the University of Florida on Snowy Plovers along the Florida Panhandle. Relevant data being collected included pair counts of Snowy Plover, nest site locations and habitat information, brood survival and movements, and dispersal information. These data were critical (a) for input into the coastal GIS database being used to identify focal areas for modeling habitat changes, and (b) as parameters for input into the metapopulation model for Snowy Plover. Dr. Fischer also obtained Snowy Plover pair count and nest-site data from Tyndall AFB and Eglin AFB, information on a planned beach nourishment project on Eglin AFB, and other available Snowy Plover data for the Panhandle, and coordinating the update process for the coastal GIS database. The overall preparation and analysis methodologies for these environmental data are found in the published and submitted papers listed in the reference section (e.g. Convertino et al., 2011a-g; Chu-Agor et. al., 2011 and 2012; Aiello-Lammens et al., 2011).

3.2 Parameterization and execution of the SLAMM Model

SLAMM (Sea Level Affecting Marshes Model) (Warren Pinnacle Consulting, Inc., Warren, VT) simulates the dominant processes involved in coastal wetland conversions and shoreline modifications during long-term SLR. Inundation (i.e. reduction in elevation due to SLR), erosion, over wash (effect of large storms on barrier island), saturation (rising of water table), and accretion are the primary processes included in SLAMM. Each wetland type (Table 1) is associated with certain elevation boundaries and conditions (e.g. salinity, tidal ranges, vegetation.) required for that specific wetland type to exist. SLAMM divides a spatial area into square cells of customized size and carries out the calculations for each cell, determining whether the cell is going to remain in the same category, or be converted to another as the sea level rises. In this application, cell size was set to a 30m horizontal resolution for the Eglin Air Force Base/Santa Rosa Island areas and a 120m grid resolution for the entire Florida Gulf Coast (Pensacola to Naples). SLAMM version 5 was used to simulate the yearly changes in the coast of Eglin AFB. Later in early 2010, a newer, open-source version, SLAMM v6, was used to simulate the yearly land cover change in the entire Gulf Coast of Florida as basis for the Florida Snowy Plover metapopulation model.

Table 1 Land cover categories used in SLAMM and their descriptions (Clough, 2010).

SLAMM Classes	Description (C-CAP NOAA Classes)
Undeveloped Dry Land	Developed Low Intensity, Developed Open Space, Cultivated Crops, Pasture/Hay, Grassland/Herbaceous
Swamp	Palustrine Forested and Scrub-Shrub (living or dead)
Cypress Swamp	Needle-leaved Deciduous Forest and Scrub-Shrub (living or dead)
Inland Fresh Marsh	Palustrine Emergents; Lacustrine and Riverine Nonpersistent Emergents
Trans. Salt Marsh	Estuarine Intertidal, Scrub-shrub and Forested
Regularly Flooded Marsh	Salt Marsh, Estuarine Intertidal Emergent
Mangrove	Estuarine Intertidal Forested and Scrub-Shrub, Broad-leaved Evergreen
Estuarine Beach	Estuarine Intertidal Unconsolidated Shores
Tidal Flat	Estuarine Intertidal Unconsolidated Shore (mud or organic) and Aquatic Bed; Marine Intertidal Aquatic Bed
Ocean Beach	Marine Intertidal Unconsolidated Shore, cobble-gravel, sand
Inland Open Water	Riverine, Lacustrine, and Palustrine Unconsolidated Bottom, and Aquatic Beds
Estuarine Open Water	Estuarine Subtidal
Open Ocean	Marine Subtidal and Marine Intertidal Aquatic Bed and Reef

A number of limitations are inherent in SLAMM and should be considered when using its results for management applications. SLAMM is neither a hydrologic model nor a sediment transport model. As such, mass conservation is not applied and the explicit movement of water and sediment is not simulated. The salinity module of SLAMM is quite simple consisting of a salt wedge. Accretion rates are important parameters in the model, but are hard to quantify in the field (Chu-Agor et al., 2011). The beach overwash function is quite uncertain as the timing and size of storms is static within the model and erosional processes in the field are difficult to predict. Because of these limitations this model should not be used to predict responses to sea level rise in specific areas. Rather, the model should be used as a screening tool to assess areas of concern and investigate possible scenarios.

3.3 Development of the habitat suitability and species distribution models

The habitat suitability for Snowy Plovers for the entire Gulf coast of Florida was modeled by calculating the probability distribution of maximum entropy (MaxEnt) (Phillips et al., 2006, 2008) subjected to the constrains of nest occurrences, land-cover, and geology as environmental variables. The habitat suitability was analyzed at different spatial resolutions by coarsening the ecogeographical layers with a majority (upscaling considering the highest presence class among groups of finer resolution grid cells) and conservative (upscaling that preserved the percentage of presence classes of sampled finer resolutions) algorithm. Detailed methodologies are provided in Convertino et al. (2011a; 2011b; 2011c and 2011f). In order to test the validity and uncertainty of MaxEnt other species distribution models were used but their performance relative to MaxEnt was poorer (Convertino et al., 2011a, c). With the aim to capture fine-scale details of the species distribution modeling a Bayesian inference was used, in particular to detect the interactions among shorebirds, tropical hurricanes, and nourishments (Convertino et al., 2011b, d).

Theoretical aspects about the distribution of the occurrences of shorebirds were also addressed, formulating a mathematical theory for characterizing those occurrences in space (Convertino et al., 2011e).

3.4 Development and parameterization of a Snowy Plover model in RAMAS-GIS

We developed a metapopulation model for Florida Gulf Coast population of Snowy Plover by estimating key demographic parameters, based on the information we have collated on this species. We determined the demographic structure (age- and sex-structured, with two age classes for each sex), mating system, and the initial spatial structure (a metapopulation with three subpopulations). We also analyzed the available data to provide initial estimates of dispersal rate, survival rate, and fecundity. The results of this task were used for running simulations to estimate the viability of the Florida Snowy Plover populations under climate change. The detailed methodology and results of these simulations are summarized in a presentation (Aiello-Lammens et al., 2010) and a published manuscript (Aiello-Lammens et al., 2011).

3.5 Global sensitivity and uncertainty analysis for environmental and ecological models

Subsequent testing efforts aimed to quantify the contribution of uncertain model inputs to the uncertainty of the outputs of a metapopulation model applied to Florida Gulf Coast Snowy Plovers. This was carried out by employing global sensitivity and uncertainty analysis (GSA/UA) using two generic (model free) methods, a qualitative Morris method and a quantitative variance-based Sobol method. The Morris method ranks the model inputs according to their importance in driving model outputs uncertainty, while the Sobol method computes the contribution of each model input to the variability of the outputs. Monte Carlo filtering was also performed in order to identify the ranges of inputs that produce a specific output as basis for possible management schemes that will ensure the continued existence of these birds. The analyses were applied to three density dependence scenarios: a ceiling-type density dependence, a contest-type density dependence, and assuming that density dependence is uncertain as to being ceiling or contest. Density dependence describes the growth of a population as a function of its current population size. In the ceiling-type density dependence, the population is assumed to grow exponential until it reaches the ceiling (i.e., all territories are occupied) and remains at that level until the population declines (due to emigration or random fluctuation) (Akçakaya, 2005). In the contest-type density dependence on the other hand, there is an unequal sharing of resources resulting in the survival and reproduction of some individuals at the expense of the others (Akçakaya, 2005). A detailed methodology and results of the model testing are found in a book chapter of the NATO conference proceedings on Climate Change (Muller et al., 2011), the published journal paper on SLAMM-based coastal habitat change projections (Chu-Agor et al., 2011), and on the evaluation of shorebird metapopulation projections with RAMAS (Chu-Agor et al., 2012).

3.6 Development of multi-criteria decision frameworks for integration of linked model/uncertainty analysis

Climate change and ecosystem issues are inherently challenging and require greater amounts of coordination, consensus, and complementarity among people, their management processes and their systems analysis tools. Multi-criteria decision analysis (MCDA) coupled with levels of risk and uncertainty assessment can help to integrate the heterogeneous scientific information (e.g., cost, beach area) with management and stakeholder value judgments. This work compares results from two MCDA software packages: Stochastic Multi-criteria

Acceptability Analysis (SMAA) and Logical Decisions. SMAA (Tervonen and Figueira, 2008) uses an outranking based method for exploring uncertainty in terms of performance criteria as well as value weights. In doing so, SMAA runs MCDA multiple MCDA simulations considering a full suite of possible weights. Logical Decisions is MCDA software similar to SMAA but runs single and multiple simulations allowing explicit input of weights. Additionally, the portfolio decision model was developed internally by the Engineer Research and Development Center (ERDC)/ University of Florida (UF) team members using Visual Basic.

The scale considered for this analysis was the entire Gulf Coast of Florida and all of the populations of Snowy Plovers therein. This scale is considered most applicable in this methodology because populations of plovers throughout the coast may mix and interbreed. Simulating that connectivity captures a more realistic picture of the effects of management practices.

The general MCDA model structure is represented in Figure 9. Here, the overarching goal is for coastal protection. A sub-goal is for Snowy Plover protection. Measures that are used to assess the goal performance include beach area, cost, public popularity, Snowy Plover carrying capacity in 2100, Snowy Plover population decline by 2100, Snowy Plover habitat suitability in 2100, and Snowy Plover risk of terminal extinction. Alternatives considered include No Action, Species Focused Beach Nourishment, Predator Exclosures, and Predator Management. Several scenarios were simulated as separate MCDA models (under the same structure) to encompass some of the uncertainty regarding the models and SLR projections. Scenarios for both 1 and 2m SLR by 2100 were simulated. In addition, ceiling and contest type density dependence was simulated in RAMAS as this was found to be an important parameter by Chu-Agor et al. (2012). This results in four MCDA models and allows for the comparison of alternatives between possible scenarios.

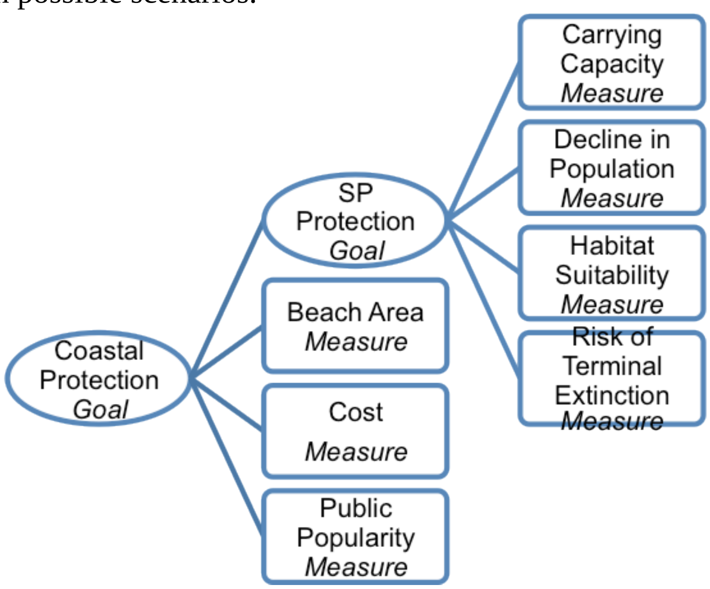


Figure 9. MCDA structure. (SP = Snowy Plover). A multi-attribute value theory is at the basis of the software used. The measures are criteria/subcriteria.

The models were linked in order to develop inputs and evaluations for the decision analysis. SLAMM projected land cover categories for most of the Gulf coast for 2010-2100. Those land cover categories (location and frequency) were merged with species location data in

order to estimate habitat available for utilization using MaxEnt. The MaxEnt outputs were then utilized as inputs in a RAMAS model for each species, in conjunction with the species growth, mortality and reproductive rates, to produce demographic predictions. The relationship between these models is considered a "soft-linkage," where one output serves as the input from the next. Soft-linking was instigated in this case so that each model would work independently of the other. "Hard-linking" of the models, such that the three run as a single unit, is a possible extension of this work. However, this task triples the complexity of addressing any output errors and limits the flexibility of the model to respond to specific, individual scenarios.

3.6.1 Alternatives

Management alternatives were developed to simulate management alternatives and their impacts on the Snowy Plover population in the Florida's Gulf Coast. The linked SLAMM/MaxEnt/RAMAS models were simulated for the Florida Gulf Coast from Pensacola to Naples at a 120m grid resolution. In the linked model process that was used (previously described), SLAMM generates the land cover maps for input into MaxEnt, which generates the habitat suitability maps, for input into RAMAS, which simulates the demographic processes for the Snowy Plover. Simulations for decision alternatives were executed for both 1m and 2m sea level rise scenarios by 2100. Both contest and ceiling type density dependence scenarios were also simulated in RAMAS. Details regarding the inputs for model simulations can be found in Chu-Agor et al. (2012) and Aiello-Lammens et al. (2011). Four alternatives are presented for the entire Florida Gulf coast: **(1) No Action, (2) Species-Focused Beach Nourishment, (3) Predator Exclosures and (4) Predator Management.**

1. No Action: In the no action alternative, no nourishment activities are simulated and demographic inputs are based on the *medium* level inputs (Table 2) from Aiello-Lammens et al. (2011).

2. Species-Focused Beach Nourishment: Currently beach nourishment plans in Florida are generally located in populated areas with little overlap with Snowy Plover nesting locations. To address the possibility of species-protection as an objective of nourishment policies, a nourishment plan based on the locations of the Snowy Plover nests was developed. In this alternative, beach nourishment maps were created based on the nesting data described in Aiello-Lammens et al. (2011). SLAMM, MaxEnt, and RAMAS were then rerun based on the nourishment alternative to investigate the impacts to the Snowy Plover population. Here, a nourishment site is designated in areas where more than one nest is found within a 2km distance. In this alternative, 161 km of total beach length is designated for nourishment. Nourishment for this alternative is simulated every 10 years until 2100. In this alternative demographic inputs are based on the *medium* inputs found in Aiello-Lammens et al. (2011)

3. Predator Exclosures: The third alternative involves simulating the use of predator exclosures to augment the fecundity of the Snowy Plover. Studies have indicated that the use of predator exclosures can increase nesting success (Colwell et al., 2008; Lauten et al., 2008). For example, Lauten et al. (2008) showed that exclosures increased the nesting success rate from 38 to 44% along the Oregon coast.

   RAMAS simulates fecundity according to $F = f \bullet S_J$, where F is equal to fecundity, f is the number of fledglings, and S_J is the juvenile survival rate. In order to represent an

increase in fecundity from the use of predator exclosures, *f* was increased and RAMAS was rerun. The value used here to simulate predator exclosures is based on the maximum value for fecundity established in Aiello-Lammens et al. (2011) (0.716) (Table 2). This parameter value was determined by Chu-Agor et al. (2012) to represent the potential for management to improve fecundity.

4. Predator/Human Management: The fourth alternative involves simulating the management of predators such as through lethal methods and limiting dog access on beaches. Studies have documented the impacts that humans have on the survivability of Snowy Plover juveniles and adults. For example, Ruhlen et al. (2003) showed that at Point Reyes National Seashore, California chick mortality was approximately three times higher on weekends and holiday than on weekdays. Collwell et al. (2008) also showed that the use of a symbolic fence in a highly trafficked area increased fledgling success from 15 to 37%. However, this increase in fledgling success was not seen consistently throughout all of their sites.

   Similar to the Predator Exclosure alternative, this alternative was based on the ranges for juvenile survival and adult survival established in Aiello-Lammens et al. (2011). The maximum values for these ranges (Table 2) were used to represent the potential for these management strategies to improve survival of Snowy Plover. As with the parameter value in the Predator Exclosure alternative, these parameter values were determined by Chu-Agor et al. (2012) to represent the potential for management to improve Snowy Plover survival. RAMAS was rerun based on these parameter values.

Table 2. Values for *medium* and maximum demographic inputs to the RAMAS model (Aiello-Lammens et al., 2011).

Input	Median	Maximum
Fecundity	0.592	0.716
Juvenile Survival	0.574	0.646
Adult Survival	0.691	0.763

3.6.2 Measures

The various state-level decision criteria to judge the success of a decision alternative include ecological metrics describing Snowy Plover population performance and risk of extinction, beach habitat area, projected alternative costs, and public popularity. It is beyond the scope of this analysis to incorporate specific damage to coastal property and commercial gain/losses that may occur from SLR scenarios.

Cost of Alternative: This metric estimates the total cost per year of an option in terms of implementation of actions. A simple linear ratio was used to determine the median cost of this scenario. The total cost for fiscal years 2012-2022 for beach nourishment in Florida's Gulf Coast, as estimated by the Florida Beach Management Plan, is $413,035,800 (FDEP, 2011). This includes feasibility studies, design, construction, and monitoring. The total length of planned critical erosion beach nourishment projects for the same time period is approximately 175km. The Snowy Plover nourishment scenario proposes 161 km of beach nourishment or 92% of the critical erosion scenario. This results in a cost of $379,992,936. The range of uncertainty for this cost was set to -25 to +50% of the median cost at the 5% and 95% confidence interval.

The cost of the predator exclosure and predator management alternatives was estimated according to Honaday et al. (2007). This document states that the estimated cost of the recovery for the western Snowy Plover along the Pacific coast is $149,946,000 plus additional costs which could not be determined. The estimated date of recovery was 2047. Accordingly, the annual cost for this management plan is $3,748,650. This plan includes predator exclosure, predator management, restricting beach access, as well as additional measures such as restricting military use, enhancing habitat, and monitoring. The estimates for the predator exclosure and predator management alternatives in this MCDA were assumed to be half the annual cost of the Honaday et al. (2007) study. An uncertain range to this cost was assigned to the cost measure of ±50% at the 5% and 95% confidence interval.

Beach Area: Beach area is an important measure for humans, Snowy Plovers, and additional ecological functions. This metric describes the total beach area remaining in 2100. Results were obtained from the SLAMM simulations of 1 and 2 m SLR as well as the No Action and Beach Nourishment scenarios. Results are reported as percent remaining beach area in 2100 (Table 3).

Chu-Agor et al. (2012) conducted an uncertainty analysis of SLAMM along a 20 km stretch of Santa Rosa Island at Eglin AFB. These results indicated a median remaining beach area at 2100 of 95 ha. The variation in these results gave a change in area from 2010 to 2100 that ranged between -10 and -100 ha with a normal distribution. From this, an uncertain bound was assigned for the beach area throughout the entire Gulf Coast at 2100 with a 95% confidence interval of ±31% of the median value of beach area.

Table 3. Percent beach remaining in 2100 for the median, 5% and 95% confidence intervals (C.I.).

Alternative/Scenario	5% C.I.	Median	95% C.I.
No Action 1m SLR	42	87	104
Beach Nourishment 1m SLR	61	96	123
No Action 2m SLR	7	69	69
Beach Nourishment 2m SLR	31	81	93

Public Popularity: This is a simple index of the public acceptance for each alternative: No Action, Beach Nourishment, Predator Exclosure, and Predator Management. The scale ranges from 0 to 2 with no change in public perception set to 1, a negative perception as a negative value, and a positive perception as a positive value (Table 4). Here, the least popular alternative is predator management as this would likely involve prohibiting dogs on beaches and possibly killing predators. Predator exclosure is more popular but still slightly negative because of the impact to the useable space on the beach. No action is considered to cause no change in public perception. Beach nourishment gives a positive change in public perception because beach goers appreciate the beach for recreation as well as habitat. These values are based on expert opinion.

Table 4. Public popularity for each alternative.

Alternative	Value
No Action	1
Beach Nourishment	1.5
Predator Exclosure	0.7
Predator Management	0.5

Snowy Plover Protection: This set of metrics describes the success of Snowy Plover protection by the final year of the SLAMM/MaxEnt/RAMAS simulations. Four metrics describe this objective: habitat suitability (ha), carrying capacity (%), decline in population (%), and risk of extinction (%).

Habitat suitability was determined from the MaxEnt results. Results were obtained from the SLAMM/MaxEnt simulations of 1 and 2 m SLR as well as the No Action and Beach Nourishment scenarios. For this measure, cells throughout the study site with a habitat suitability equal to and greater than 0.6 (indicating nesting habitats) were summed. Results are reported as area of habitat suitability in hectares in 2100 (Table 5). Uncertain bounds for the simulation scenarios were set using the same data and method described in the beach area measure and assigned a 95% confidence interval of ±31% of the median value of habitat suitability.

Table 5. Hectares of suitable habitat (≥ 0.6) in 2100 for the median, 5% and 95% confidence intervals (C.I.).

Alternative/Scenario	5% C.I.	Median	95% C.I.
No Action 1m SLR	4893	7091	9289
Beach Nourishment 1m SLR	5432	7873	10314
No Action 2m SLR	4176	6052	7928
Beach Nourishment 2m SLR	4954	7180	9406

Carrying capacity was determined from the RAMAS results. Results were obtained from the SLAMM/MaxEnt/RAMAS simulations of 1 and 2 m SLR as well as the No Action and Beach Nourishment scenarios. Results are reported as the percent carrying capacity remaining of individuals for the Gulf Coast in 2100 (Table 6). Uncertain bounds for the simulation scenarios were set using the same data and method described in the beach area measure and assigned a 95% confidence interval of ±31% of the median value of habitat suitability.

Table 6. Percent carrying capacity remaining in 2100 for the median, 5% and 95% confidence intervals (C.I.).

Alternative/Scenario	5% C.I.	Median	95% C.I.
No Action 1m SLR	55	80	105
Beach Nourishment 1m SLR	65	95	124
No Action 2m SLR	43	62	81
Beach Nourishment 2m SLR	56	81	107

Decline in population was determined from the RAMAS results. Results were obtained from SLAMM/MaxEnt/RAMAS simulations of 1 and 2 m SLR scenarios, No Action and Beach Nourishment scenarios, as well simulations for contest and ceiling type density dependence.

Results are reported as the percent decline in population for the Gulf Coast between 2010 and 2100 (Table 7). Uncertain bounds for the simulation scenarios were set according to the stochastic set of runs produced in RAMAS and reported as plus/minus one standard deviation. This range is intended to represent the natural variability due to the stochastic nature of demographics, catastrophes, as well as temporal and spatial relationships, not the uncertainty of the model itself.

Table 7. Percent population remaining in 2100 for the median, 5% and 95% confidence intervals (C.I.).

Alternative/Scenario	5% C.I.	Median	95% C.I.
No Action 1m SLR contest	3	36	67
No Action 1m SLR ceiling	85	94	100
No Action 2m SLR contest	3	35	66
No Action 2m SLR ceiling	81	92	100
Beach Nourishment 1m SLR contest	-7	26	60
Beach Nourishment 1m SLR ceiling	86	94	100
Beach Nourishment 2m SLR contest	2	31	63
Beach Nourishment 2m SLR ceiling	81	91	100
Predator Exclosures 1m SLR contest	6	37	65
Predator Exclosures 1m SLR ceiling	20	50	77
Predator Exclosures 2m SLR contest	22	46	71
Predator Exclosures 2m SLR ceiling	31	51	72
Predator Management 1m SLR contest	6	36	65
Predator Management 1m SLR ceiling	18	48	75
Predator Management 2m SLR contest	31	50	72
Predator Management 2m SLR ceiling	26	49	52

Risk of extinction was also determined from the RAMAS results. Results were obtained from SLAMM/MaxEnt/RAMAS simulations of 1 and 2 m SLR scenarios, No Action and Beach Nourishment scenarios, as well simulations for contest and ceiling type density dependence. Results are reported as risk of decline to 20 individuals in 90 years (from 2010 to 2100) (Table 8). Uncertain bounds for the simulation scenarios were again set according to the stochastic set of runs produced in RAMAS and reported as plus/minus one standard deviation. This range is intended to represent the natural variability due to the stochastic nature of demographics, catastrophes, as well as temporal and spatial relationships and not the uncertainty of the model itself.

Table 8. Risk of extinction in 2100 for the median, 5% and 95% confidence intervals (C.I.).

Alternative/Scenario	5% C.I.	Median	95% C.I.
No Action 1m SLR contest	0	0.1	2.9
No Action 1m SLR ceiling	68	70.8	73.6
No Action 2m SLR contest	0	0.1	2.9
No Action 2m SLR ceiling	59.7	62.5	63.5
Beach Nourishment 1m SLR contest	0	0.3	3.1
Beach Nourishment 1m SLR ceiling	68.8	71.6	74.4
Beach Nourishment 2m SLR contest	0	0.1	2.9
Beach Nourishment 2m SLR ceiling	59.5	62.3	65.1
Predator Exclosures 1m SLR contest	0	0.1	2.9
Predator Exclosures 1m SLR ceiling	0.9	3.7	6.5
Predator Exclosures 2m SLR contest	0	0.1	2.9
Predator Exclosures 2m SLR ceiling	0	1.8	4.6
Predator Management 1m SLR contest	0	0.1	2.9
Predator Management 1m SLR ceiling	0	2.4	5.2
Predator Management 2m SLR contest	0	1.9	4.7
Predator Management 2m SLR ceiling	0	1.9	4.7

3.7 Spatial portfolio decision analysis

The portfolio decision analysis is composed of three parts: an MCDA, a risk model, and a multiobjective linear optimization model (Convertino et al, 2012b). We used a multi-attribute value model (MAVT) for the MCDA model of the human and natural assets considered. The MCDA values are potentially calculated as a function of the hazard and they are also representative of the local vulnerability and exposure. For the species, the MCDA considers the local habitat and population needs. The risk model considers the overall metapopulation risk of extinction.

The MCDA value for the species considered is defined as:

$$E_{i,j}(x,t) = \sum_{k=1}^{n} w_{j,k}\, c_{i,j,k}(x,t) \tag{5}$$

For restoration alternative *i*, species *j*, and criteria *k*. *c* is the set of criteria of the MCDA for species *i*. The criteria can assume different values in space and time. *w* is the weight on criteria assigned by expert-judgment. Criteria include the biocomplexity measures shown for example in Figures 9 and 10 and other relevant biological factors of the species and its habitat. The values of criteria are defined at the “management pixel” scale whose size constitutes a

tradeoff between socio-ecological needs and effective management practices. Thus, the habitat suitability is averaged within each management pixel. In our case the ecogeomorphological variables (land cover and habitat suitability) are calculated at a resolution of 120 m. The resolution of the management pixel is 600 m, that is, five times larger than the 120 m resolution. We selected this management scale considering the scale at which it is reasonable and effective to change restoration alternatives.

For the human assets (i.e. the military training and recreational use in our case) the MCDA considers the local habitat features, and the risk model considers the probability that such areas are not available for their use. The social value is defined as:

$$S_{i,j}(x,t) = \sum_{k=1}^{n} w_{j,k}\ c_{i,j,k}(x,t) \tag{6}$$

For restoration alternative i, species j, and criteria k. c is the set of criteria of the MCDA for species i. The criteria can assume different values in space and time. The *w* components of equation (6) is the weight on criteria assigned by expert-judgment. In the case of human use of habitat for the Florida Gulf coast, we considered only recreational use and military use.

The social and ecological values of human and natural assets, which are defined in the previous equations, are modified to consider the probability of success of the restoration alternatives on these assets. In a decision science viewpoint, each decision of restoration alternative is characterized by a probability of failure and success. Thus, we define the expected ecological and social value as:

$$E^*_{i,j}(x,t) = [1 - v_j\ k_{i,j}] \times E_{i,j}(x,t) \tag{7}$$

$$S^*_{i,j}(x,t) = [1 - v_j\ k_{i,j}] \times S_{i,j}(x,t) \tag{8}$$

Where k=1-u, in which u is the utility of restoration i for species j, and v is the vulnerability of the metapopulation. The vulnerability is the probability of extinction or decline of the metapopulation that contributes to the total probability of failure of each intervention. In fact, one can assume that the success of a restoration is a function of the conservation status of a metapopulation; the higher the vulnerability of the species, the higher the likelihood of failure of a restoration alternative. While this is certainly not always the case, we can say that this is on average true. The probability of extinction/decline of species (which is indeed a vulnerability measure because it is independent of the hazard and exposure) is derived from the IUCN index and the SAFE index and normalized according to the maximum IUCN and SAFE indices of the species considered. For the Snowy Plover this vulnerability is determined by RAMAS used in our metapopulation study.

The multiobjective optimization model selects the best set of restoration alternatives that are economically feasible and that maximize the overall socio-ecological value of the assets considered. In a Pareto efficient economic system no allocation of given resources can be made without making at least one individual worse off. Given a set of choices and a way of valuing them, the Pareto frontier, or Pareto set or Pareto front, is the set of choices that are Pareto

efficient. The socio-ecological value (SEV) of a portfolio set of restoration alternatives is defined as the Euclidian distance of the value of ecological and human assets

$$SEV = \sqrt{\sum_{j=1}^{m}(E^*_{i,j}\ w_j)^2 + \sum_{j=1}^{p}(S^*_{i,j}\ w_j)^2 + \mu(x,t)^2} \tag{9}$$

Where E* and S* are expected ecological and social values respectively, w is the weights of stakeholders for species or human asset j, and m is a spatiotemporal noise added to the equation to consider uncertainty in the estimation of the input factors of the models. The factor m in equation (9) is random white noise applied to the whole Florida domain. The mean is 0.5 and the extremes are in the range [0,1]. The standard deviation of the habitat suitability (estimated by MaxEnt) can be considered also for the characterization of the spatial uncertainty. We prefer to model the uncertainty as a white noise process because we want to capture that uncertainty that is related also to the assessment of the cost of the alternatives and the values of the MCDA criteria.

The cost of a set of restoration alternatives is defined as:

$$C = \sum_{i,j} C_{i,j}(x,t) \tag{10}$$

Where $C_{i,j}$ is the cost of the alternative *i* of asset *j*.

In the case of the Pareto optimization unconstrained to the resources, if SEV(S1) ≥ SEV(S2) and C(S1) < C(S2), then the portfolio combination X1 dominates X2. The portfolio set ``S'' is then defined by a socio-ecological value and a cost. A suboptimal set is defined such that C(S1) < C(S2) and SEV(S1) < SEV(S2). In our portfolio analysis, when there is an overlap of restoration alternatives for two or more assets in the same management pixel the duplicates are dropped from the portfolio set.

4. Results and Discussion

This section highlights the different research results as organized by groups of specific tasks.

4.1 Coordinate with coastal Florida military installation personnel (and research partners) to obtain updated climate, landscape and TER-S data for the entire Florida Gulf Coast.

4.1.1 Meetings with installation personnel

The first research tasks highlight the primary step of gathering and assessing existing climate, landscape and TER-S data for subsequent model testing and development. Our research team met twice with natural resource managers and planners from Eglin AFB to discuss progress on the project and its linkage to local base decisions. These meetings highlighted practical issues on management choices and potential expansion of mission operations on Santa Rosa Island (SRI). Many of the base activities have multiple objectives and require decision making in time scales varying from days to years ahead. In June 2010, the Eglin AFB managers provided additional planning and infrastructure reports to aid our team in developing realistic, mission-relevant decision structures for further discussions.

After our September 30, 2010 meeting at Eglin AFB, we developed simple management metrics (Land, Marsh, Water) for use in executive summaries with greater detail provided within the Vulnerability Report and its Technical Appendices. Another important feature for exploration is the concept of "training windows" in terms of time and space over SRI. Instead of laying out detailed training scenarios for our simulations, we were advised to provide spatial and temporal information towards where general training events were possible. This "window" paradigm allows for base managers to see what areas are available for their own training needs in a basic footprint. As a result of these conversations, we simulated the entire Eglin AFB area at 30m resolution so that all areas may be incorporated into the training window methodology. Originally our SLAMM/vulnerability simulations covered only 10 km inland. In addition, Eglin AFB staff expressed concern about future road infrastructure on SRI, access to the island, and vulnerability of existing fiber-optic networks running length of the island (subsurface). While the research team would not specifically simulate the effects of SLR upon these local-scale, hard-infrastructure items, the research team did agree that it may be useful to create enlarged SLAMM output maps showing SLR/habitat changes in some areas of particular management interest.

4.1.2 Climate effects on selected TER-S

Historical and future projected climate data were used in two ways: (1) the effect on habitat suitability and (2) direct effects on shorebird populations. The results have been report in the per-reviewed literature as Convertino et al., 2011(b, d). The projections indicate climate change is associated with fewer, more intense cyclones. That pattern of changes is likely to have a negative impact on Snowy Plover. The nesting population of birds is seven-fold higher following a cyclone. Therefore, the less frequent and more intense projection negatively impact the nesting population averaged over time. Beach renourishment work allows identification of the habitat characteristics associated with each species. For example, suitable habitats for Snowy Plover are beach area containing sparse low vegetation in the foredune area and low and uneven slope to the surface. These land cover specifics allow interpretation of the SLAMM model land cover by the MaxEnt habitat suitability model.

4.1.3 Shorebird literature review for model development

We based our demographic model on breeding season census data collected in both Florida (Sprandel et al., 1997, 2000; Himes et al., 2006; Lamonte et al., 2006) and the Pacific Coast of the United States (i.e. Western Snowy Plover) (Colwell et al., 2008; Knapp & Peterson, 2008; Lauten et al., 2008; Page et al., 2008) as well as on data presented in published studies from Pacific Coast US populations (Stenzel et al., 1994, 2007; Colwell et al., 2005, 2007; Page et al., 2009). We constructed an age- and sex-structured matrix model with two age classes (juvenile and adult), parameterized according to a pre-reproductive census and polyandrous mating system. We assumed a 1:1 initial sex ratio based on observations from several studies (Mullin, 2006; Stenzel et al., 2007; Page et al., 2009). Although the initial sex ratio is 1:1, the sex ratio can get skewed in small populations due to demographic stochasticity, which in turn may affect reproduction. To account for this effect, we included separate male and female stages in the model. We calculated variability in survival and fecundity due to environmental fluctuations by subtracting estimated demographic variance from total variance observed in long time series of these variables, using the methods of Akcakaya (2002) with data from (Colwell et al., 2008; Lauten et al., 2008; Page et al., 2008; Stenzel et al. (2007).

Density dependent factors play a role in population dynamics for this species (Page et al., 2009), and provide the link between the habitat model and the demographic rates. Density dependence is implemented by reducing demographic rates as a function of population size and carrying capacity (K) at each time step, with K determined from habitat maps projected by the SDM as described above. The available data were not sufficient to precisely quantify density dependence. Thus, we selected two types of density dependence: Ceiling, which assumes that the population grows according to the stage matrix until it reaches the carrying capacity, and Contest, which requires specifying a maximum population growth rate, Rmax, at low population sizes, and assumes Beverton–Holt type density effects on growth rate as the population approaches its carrying capacity.

Because of a lack of data for dispersal of Snowy Plover in Florida, we estimated dispersal rates based on data collected from populations on the Pacific Coast of the United States, where adult Snowy Plovers show high breeding site fidelity. There is substantial dispersal within and between breeding seasons (Page et al., 2009), with larger distances covered between breeding seasons (Stenzel et al., 1994). In addition, natal dispersal is common (Colwell et al., 2007; Stenzel et al., 2007). We parameterized a dispersal–distance function to fit the observed dispersal trends. We then adjusted dispersal rates for each population by scaling dispersal from larger populations to small populations by the ratio of carrying capacities as outlined in (Akcakaya & Raphael, 1998). This correction yields asymmetric dispersal rates, such that the dispersal rate from larger populations to smaller populations is smaller than the reciprocal dispersal, decreasing the number of estimated dispersers from the large population. If such a correction is not applied, small populations may act as sink populations in the model simulation, resulting in pseudosink dynamics that inappropriately increase the risk of extinction for a species. Our dispersal rate estimates are consistent with the small amount of data collected on dispersal of Snowy Plover between the Panhandle and Peninsula populations in Florida (R. Pruner, personal communication).

The detailed results of these simulations are summarized in a presentation (Aiello-Lammens et al., 2010) and a published manuscript (Aiello-Lammens et al., 2011).

4.2 Gather and assess available climate, land use, SLR and habitat information for preliminary vulnerability analyses for selected bases along the Florida Gulf Coast.

4.2.1 SLAMM model testing and sensitivity/uncertainty analysis

This effort applied a generic evaluation framework consisting of a screening and variance-based global sensitivity and uncertainty analyses to simulate changes in the coastal habitats of the barrier island in Eglin AFB in order to: (1) identify the important input factors and processes that control SLAMM output uncertainty; (2) quantify SLAMM's global output uncertainty and apportion it to the direct contributions and interactions of the important input factors; and (3) evaluate this new methodology to explore the potential fate of the coastal habitats of the study area. Results showed that four input factors (DEM vertical error for the lower elevation range, historic trend of SLR, accretion, and sedimentation rates) controlled 88-91% of SLAMM's output variance in predicting changes in the beach habitat of Eglin AFB. The most dominant processes governing the fate of the coastline of the study area were inundation (i.e. reduction in elevation due to SLR) and accretion/sedimentation. Interestingly, for lower elevation habitats (salt marsh, tidal flat, and beach), results showed possible gains or losses of these habitats depending on the relative strength of these processes resulting from the combination of input factors within their proposed uncertainty ranges. Higher-elevation habitats (swamps and inland fresh marsh) showed a decrease in area over 100 years of simulation. Detailed results are found in Chu-Agor et al. (2012).

4.3 Develop and test system models to assess coastal vulnerability and habitats in and around Florida Gulf Coast military installations.

These research tasks focused on the construction and/or parameterization of three model types, SLAMM, a species distribution model (MaxEnt) and the RAMAS-GIS model.

4.3.1 Species distribution model development and analysis

The following points are summarized from the results obtained though the species distribution modeling and theoretical analysis. However a compendium of results is found in Convertino et al., 2011g.

The habitat suitability at a point used as a proxy for the habitat use was proven to be scale- and species- dependent but resolution invariant. The resolution invariance of the habitat suitability patterns (HS geographical range) is realized when the physical habitat is no longer preserved by the grid resolution coarsening. For Snowy Plovers, this means that the barrier islands are represented at each resolution. The threshold of the resolution that guarantees the resolution invariance is a function of the environmental morphology of the physical habitat (Convertino et al., 2011a).

The Coastal Change Analysis Program data from the National Oceanic and Atmospheric Administration (C-CAP-NOAA) data offered the best land-cover data for our modeling because it decreased the objective uncertainty regarding the spatial structure of the coastal ecosystem, thus reducing the temporal gap within the occurrences data, and subsequently diminishing the subjective uncertainty in the conversion of the land-cover classes to the modeled classes (Convertino et al., 2011c).

Based on the 2006 winter and breeding season monitoring, Tyndall AFB was confirmed to be the hotspot of shorebird species richness in Florida, both for resident and migratory birds. The differences in the breeding and wintering distribution of the Snowy Plover population (in the Panhandle, 80 and 60% in the breeding and winter seasons respectively; in the Peninsula, 20 and

40% respectively) and the almost unaltered total pair count can potentially confirm the predicted movement of Snowy Plovers (~20%) to the lower and warmer latitudes of the Peninsula beaches during the winter (Convertino et al., 2011d).

The habitat suitability model based on MaxEnt (Phillips et al., 2006, 2008) did not demonstrate consistent differences between the habitat preference of Snowy Plovers during breeding and winter seasons. During summer, Snowy Plovers may utilize beaches less than in the winter, possibly because bayside and overwash habitats are more proximal to brood-rearing habitat (Convertino et al., 2011d).

A negative feedback was found between Snowy Plover, Piping Plover, and Red Knot and historical nourishment projects. Results based on spatio-temporal Bayesian inference show that it was 2.1, 3, and 1 times more likely that a region was not a wintering ground following a year with a sand replenishment event for Snowy Plover, Piping Plover, and Red Knot, respectively (Convertino et al., 2011d).

We showed that favorable nesting areas along the coastline are located in regions impacted relatively more frequently by tropical hurricanes. The odds of Snowy Plovers nesting in these areas during the spring following a hurricane impact are seven times higher compared to the odds during the spring following a season without a hurricane (Convertino et al., 2011b). The result is useful for metapopulation models that often assume an *a-priori* negative feedback among shoreline-dependent species and tropical hurricanes. This relationship allows us to estimate more correctly the abundance of Snowy Plovers without any catastrophic event affecting the population of birds.

We described the coupled self-organization of the predicted habitat patches of these imperiled shorebirds with the geomorphological changes of the shoreline due to climate change. The ecosystem was modeled for a 2-m SLR by 2100 by scaling up the IPCC A1B projection (i.e, using IPCC A1B projection to compute the SLR in every time step). A scaling relationship between the fractal dimensions of the suitable patches and of the species-dependent habitat coastline was detected. Despite the changes in the coastline due to fragmentation, habitat loss, and patch connectivity, shorebirds self-organize preserving a power-law distribution of the patches that emerge as scale-free maximum-entropy patterns (Convertino et al., 2011f).

4.3.2 Involving biocomplexity: computational and theoretical achievements

Relationships among biological, ecological, geomorphological, and climatologic variables have been investigated throughout the study. Convertino et al. (2011b and 2011d) investigated the relationships among nesting and wintering probability of shorebirds and tropical cyclones, beach nourishment interventions, and the correlation among the fractal dimensions of the patches and of the coastline. These relationships show the intercorrelations between biological and geomorphological processes that can be used in multiscale models.

In Figure 10 (a) we report the analysis between the probability of occurrence of tropical cyclones and the probability of occurrence of a nesting ground. This relationship is defined by the odds ratio that is the ratio of the odds of a nesting ground in the spring following a year with at least one tropical cyclone to the odds of a nesting ground in the spring following a year without a tropical cyclone. The median odds ratio is 7 and the mean is 11. Figure 10(b) is the posterior probabilities of absence $P(A > a)$ of the odds ratio for Snowy Plover in the breeding season, and Snowy Plover, Piping Plover, and Red Knot in the wintering season. The odds ratio is the ratio of the odds of a nesting or wintering ground in the spring following a year with at least one renourishment event to the odds of a nesting or wintering ground in the spring following a year without a renourishment intervention. For the breeding Snowy Plover the

median odds ratio is 2.5 and the mean is 4.9. For the wintering Snowy Plover, Piping Plover, and the Red Knot the median odds ratio is 2.3, 3.1, and 0.8 respectively.

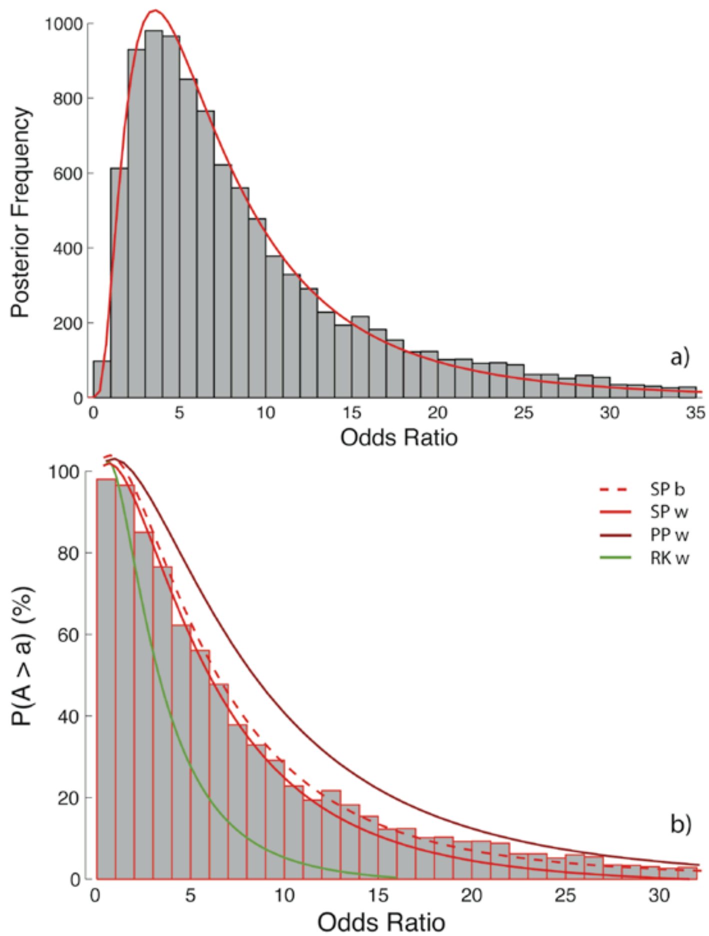


Figure 10. Bayesian inference model for Snowy Plover vs. tropical cyclones and beach renourishment. (a) Posterior frequencies of the odds ratio considering the odds of a nesting ground in the spring following a year with at least one tropical cyclone to the odds of a nesting ground in the spring following a year without a tropical cyclone. (b) Posterior probabilities of absence P(A > a) of the odds ratio for Snowy Plover in the breeding season, and Snowy Plover, Piping Plover, and Red Knot in the wintering season. The odds ratio is the ratio of the odds of a nesting or wintering ground in the spring following a year with at least one renourishment event to the odds of a nesting or wintering ground in the spring following a year without a renourishment intervention.

Figure 11, as in Convertino et al. 2012f, shows the correspondence between the fractal dimension of the suitable patches and the fractal dimension of the species-dependent habitat coastline. The fractal dimension can be used as warning signal to assess the status of the shorebirds. The higher the fractal dimension, the higher the fragmentation will be. Because high values of the fractal dimension of the coastline imply a more rugged coastline, environmental managers may decide for a renourishment intervention based on this metric. In fact, nourished

coastlines generally tend to be straighter than highly eroded coastline. In our study, the fractal dimension is used as one of the environmental criteria in the multi-criteria decision analysis within the portfolio model.

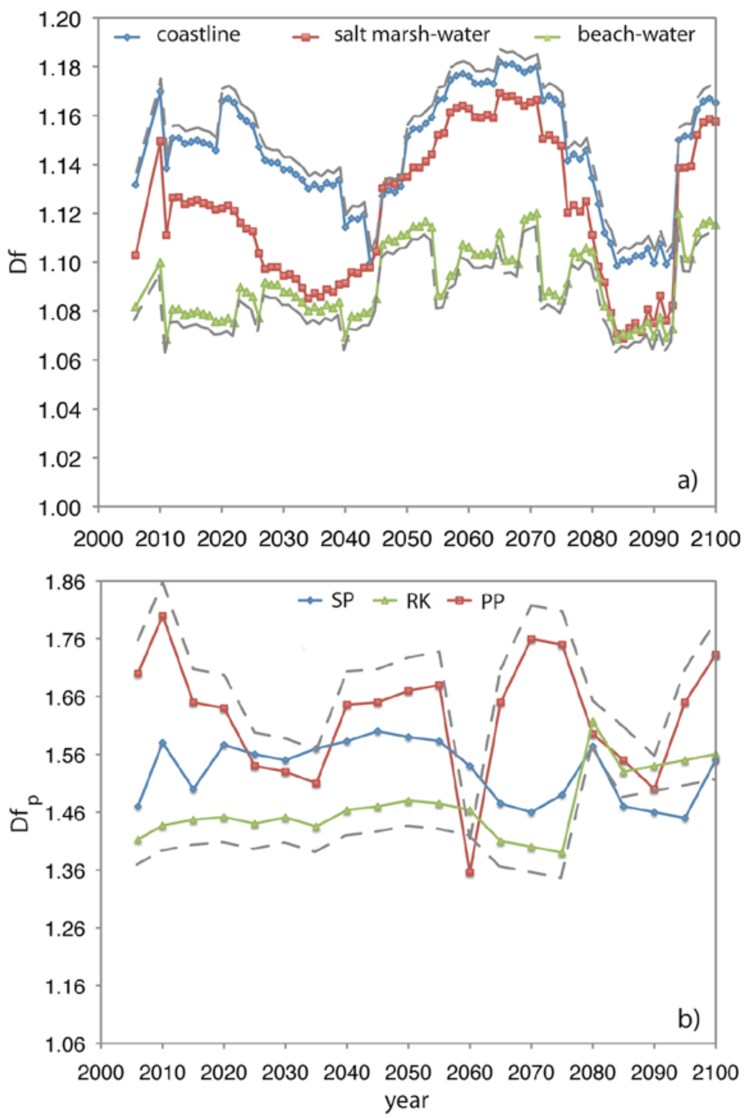


Figure 11. Fractal dimension time-series of the shorebirds patches and of the Florida Gulf coastline. (a) Time series of the fractal dimension Df of the coastline (blue line) and of the salt-marsh (red) and beach (green) habitat coastlines, determined by the box-counting algorithm. (b) Fractal dimension Dfp in time of the patches for Snowy Plover (blue dots), Piping Plover (red), and Red Knot (green) derived from the Korcak's law. The gray line represents the 95 percent confidence interval.

4.3.3 Metapopulation model development

The impact of climate change, via SLR, on the population of Florida Snowy Plovers was investigated by integrating a habitat model (SLAMM), a habitat suitability model (MaxEnt), and a demographic population model (RAMAS GIS). SLAMM simulates changes in the habitat due to long term SLR. The land cover maps generated from SLAMM were converted to continuous

presence probability maps based on environmental variables (e.g., projected land cover and geological factors) and recorded shorebird occurrences (Convertino et al. 2011a) using MaxEnt. The demographic model was then developed in RAMAS GIS (Akcakaya 2005), which simulates the dynamics of a metapopulation with a dynamic spatial structure, and a stochastic stage-structured model for each subpopulation of the metapopulation. Thus, it integrates demographic dynamics (i.e., survival and reproduction) and habitat dynamics (i.e., changes in habitat quality) into population projections. The demographic dynamics were estimated using population data from the Florida Gulf Coast Snowy Plover population and the Western Snowy Plover. This integrated modeling framework projected that Snowy Plover population size will decline faster than the area of habitat or carrying capacity, demonstrating the necessity of incorporating population dynamics in assessing the impacts of SLR on coastal species (Aiello-Lammens et al., 2011).

4.3.4 Global sensitivity and uncertainty analysis of the metapopulation models

The sources of uncertainty in the outputs depended strongly on the type of density dependence considered in the model. In general, uncertainty in the outputs highly depends on the uncertainty in stage matrix elements (fecundity, adult survival, and juvenile survival), dispersal rate from the “big bend” region of Florida (Gulf coast region between the peninsula and panhandle) to the Panhandle population, the maximum growth rate, and density dependence type. Further analysis showed that adopting management options to limit the rate of extinction of Florida Gulf Coast Snowy Plover would be challenging. In order to increase the final average population of Snowy Plovers, management schemes should be implemented to increase the maximum growth rate. Future studies should focus on quantifying the density dependence of Snowy Plover since this is the main driver of uncertainty in the model. Results also suggested that investigating the presence of Snowy Plovers in the “big bend” region may be important. Detailed results from this section are described in Chu-Agor, et al., (2012).

4.4 Task 10: Conduct vulnerability analysis based on current climate, land use and habitat databases.

Climate change (via SLR and altered weather patterns) is expected to significantly alter low-lying coastal and intertidal areas, which provide significant training areas for military installations as well as critical habitats for a variety of shoreline-dependent organisms. The physical changes that will be brought about by SLR to the coast of Eglin AFB are still unknown. These changes can significantly affect operations within coastal areas as well as considerably impact the population of shoreline dependent organisms and the coastal ecosystem as a whole. The exposure of the land cover of Eglin AFB and its coastline to SLR was evaluated to assess the vulnerability of each land cover category. Changes in the land cover were simulated using SLAMM version 6 at different SLR projections (0.2, 0.5, 1.0, 1.5, and 2.0 m) assuming a total simulation period between 2010 and 2100. SLAMM simulates the changes in the land cover due to inundation (i.e., reduction in elevation due to SLR), erosion, over wash (effects of large storms), saturation (rising water table), and accretion/sedimentation. Eglin AFB results were also compared against the same SLR projections at Tyndall AFB and the entire Gulf Coast of Florida (Pensacola to Naples).

In general, the habitats at Eglin AFB experienced minimal losses not exceeding 0.2% of its 2010 initial area. However, the marshes in Santa Rosa Island (SRI) are the most impacted category by SLR posting a maximum loss of 18% (30 ha) during the first 30 years. This is followed by the beach habitat incurring a loss at the end of the century amounting to 1.7% (24

ha). The most vulnerable land cover categories along the Eglin AFB coast, posting the highest percent loss between 2010 and 2100, are the regularly flooded marsh (25% loss) and the estuarine beach (11% loss). The tidal flat underwent a more dynamic inland migration compared to the rest of the categories. Overall, Eglin AFB is more stable compared to Tyndall AFB and the whole Gulf Coast of Florida manifesting the least changes between 2010 and 2100 at SLR = 2.0 m in all land cover categories except the tidal flat. This report provides a detailed assessment of the exposure of the different land cover categories comprising the coastline of Eglin AFB to SLR at the end of the century. Using the information in this report, the potential impacts of these changes in the habitats to the ecosystem and to humans can be assessed for future conservation and protection efforts.

4.4.1 Exposure of Eglin AFB/SRI to SLR

The present land cover map (2010) of Eglin AFB was simulated based on the land cover map of 2006 (NOAA, 2006) at a 30 m x 30 m resolution. The National Oceanographic and Atmospheric Administration (NOAA) land cover classifications were converted to SLAMM classifications before the simulations were run. For example, the NOAA upland needle-leaved deciduous forests and scrub-shrub land cover types were converted to cypress swamp in SLAMM (Table 1). The eustatic SLR simulated by SLAMM for 2010 at different projected SLR (i.e., at 0.2, 0.5, 1.0, 1.5, and 2.0 m by 2100) averaged to 0.02 m with a standard deviation of 0.015. This eustatic SLR value did not produce any significant difference between the present land cover (2010) and that of 2006. In fact, the simulated land covers for the first decade did not exhibit significant differences among the different SLR projections used. The study areas are comprised of 13 categories which include both land masses and open water (Table 1). Developed areas were masked (white patches in Figure 12) as SLAMM can assume that developed land will be defended against SLR (Clough, 2010). Masking the developed areas prevents them from being converted to another category and thus not affecting the areas of these categories. With this assumption and masking, all existing infrastructure areas are maintained at current levels, only undeveloped land is allowed to change with SLR.

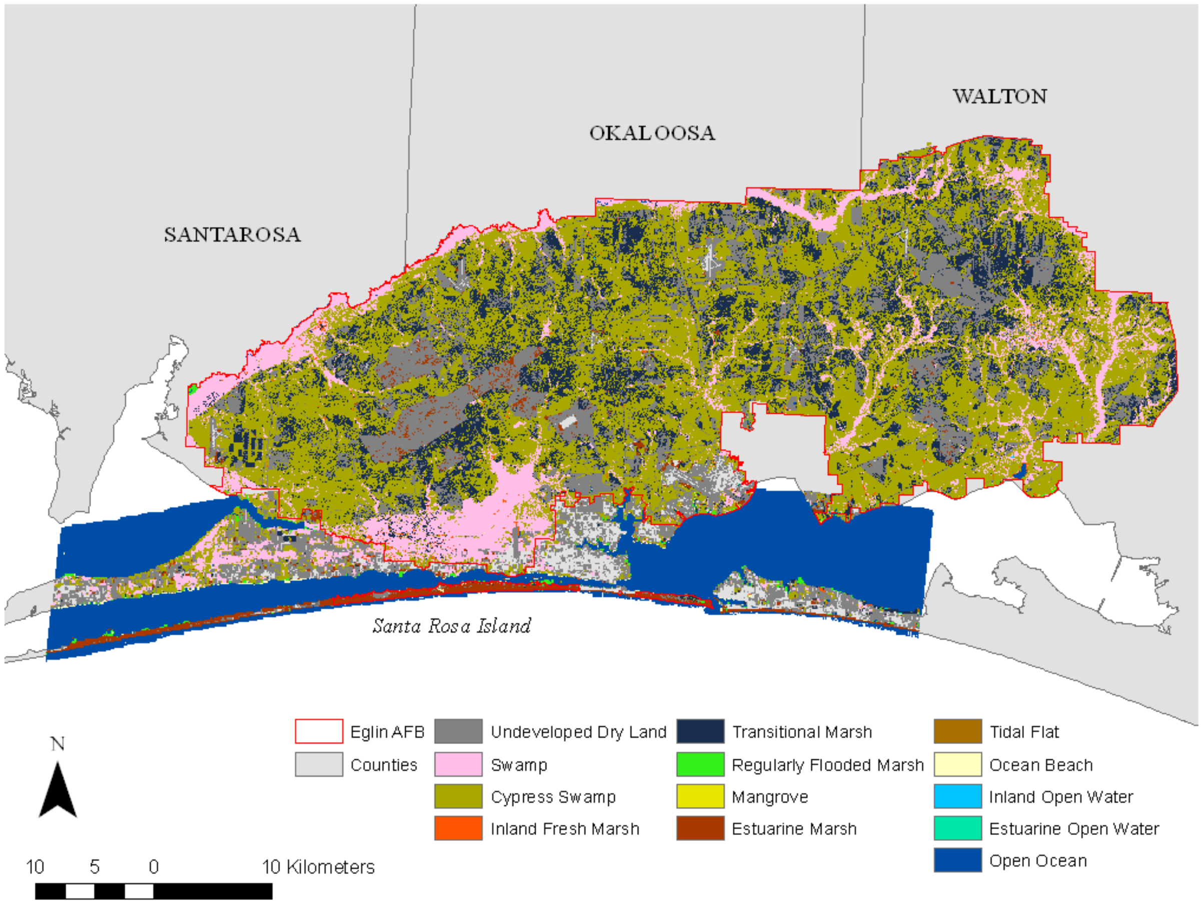
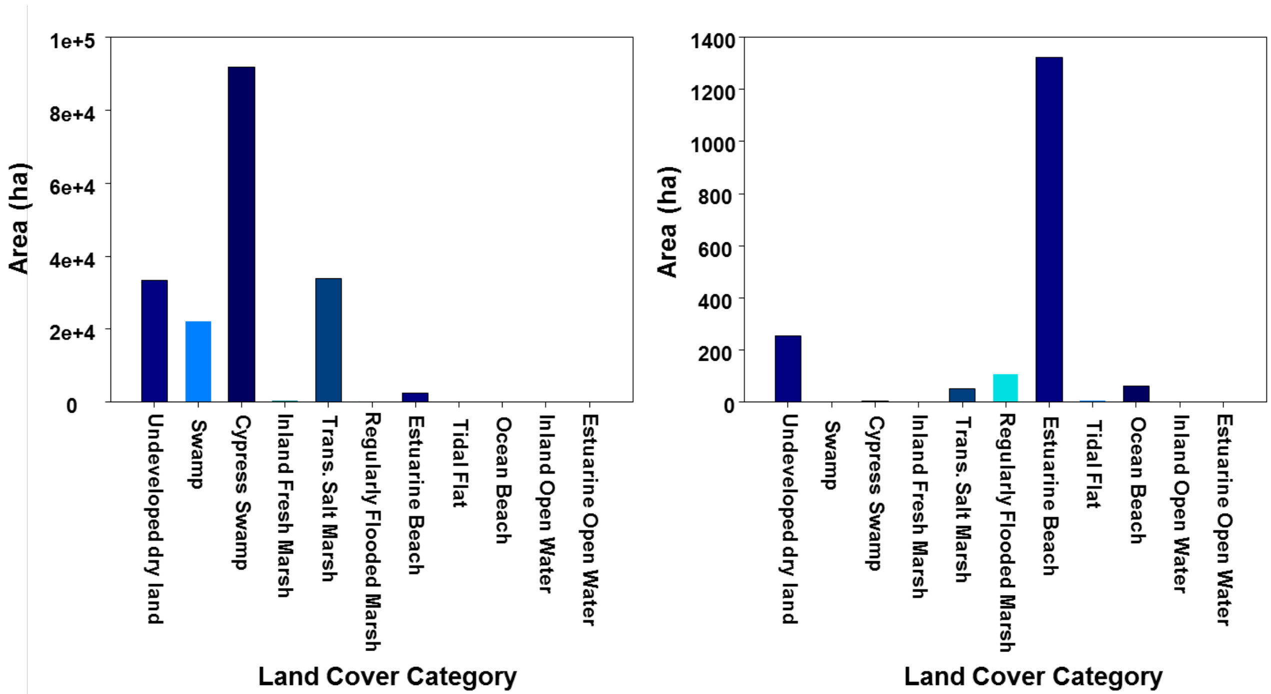


Figure 12. Land cover of the study areas (NOAA, 2006): (a) the whole military installation of Eglin AFB including Santa Rosa Island at 30 m x 30 m resolution; (b) Santa Rosa Island at 30 m x 30 m resolution; and (c) a 74-km stretch of coastline encompassing the coastline of Eglin AFB at 120 m x 120 m resolution.

The total Eglin AFB area simulated was 185,270 ha dominated mostly by Upland/"Cypress swamp" (49%) (Figure 13a). Undeveloped dry land and transitional salt marsh contribute 18% each to the total area while swamp contributed 12%. Other land cover categories occupy one percent or less of the total area. Eglin AFB also includes a portion of the Santa Rosa Island (SRI) which is predominantly estuarine beach (72%) with some patches of undeveloped dry land and marshes (Figure 13b).



(a) Eglin AFB **(b) Santa Rosa Island**

Figure 13. Areas of the land cover categories in (a) all of Eglin AFB and (b) Santa Rosa Island.

SLR projections have varying effects on the coastal land cover categories of Eglin AFB. Some land cover categories will experience a considerable change while others will be less affected by the different projections. In this report, vulnerability was associated with the decrease in the area of the land cover category since this decrease translates to a possible threat not just to the organisms living there but also to nearby infrastructure. In SLAMM, the decrease in area of a given land cover category results from the conversion of its cells, by inundation and/or erosion (equations 3 and/or 4), to another lower-elevation category. This is referred to as wetland migration. SLAMM follows a decision tree which determines the fate of the cell under the process of inundation and erosion based on factors like elevation boundaries, salinity, proximity to open water, etc. (Clough, 2010). The resulting area from SLAMM is the net area of the category, i.e., cells gained from higher elevation categories minus cells lost to lower elevation categories.

The changes in land area between 2010 and 2100 considering the different SLR projections are summarized in Figures 14 through 18. These figures show the area of five groups of habitats (undeveloped dry land, swamp, marsh, beach, and water) for Eglin AFB and SRI simulated every year.

Undeveloped dry land

Undeveloped dry land normally converts to transitional salt marsh, ocean beach, or estuarine beach depending on its proximity to open water. In some cases when the groundwater table rises higher than the elevation of the land, saturation may occur and the undeveloped dry land converts to the nearest marsh, swamp, or fresh-water type between the dry land and the open ocean. In theory, undeveloped dry land will not convert directly to open water. However, it can convert to another category that will eventually end up as open water.

In general, the undeveloped dry land is less likely to be affected by SLR compared to other habitats closer to the water edge. The undeveloped area on Eglin AFB (Figure 14a) did not manifest any change until around 2025 where a rapid decline was observed until 2050. However, this decline is less than 0.2% (67 ha) of the area. After 2050, the area remained approximately the same except at SLR = 2.0 m. The different SLR projections did not show any significant effects on the area of the undeveloped dry land except for SLR = 2.0 m from 2080 onwards where a deviation from the other SLR projections was observed (Figure 14a). Again the decrease in area within this period did not exceed 0.2%.

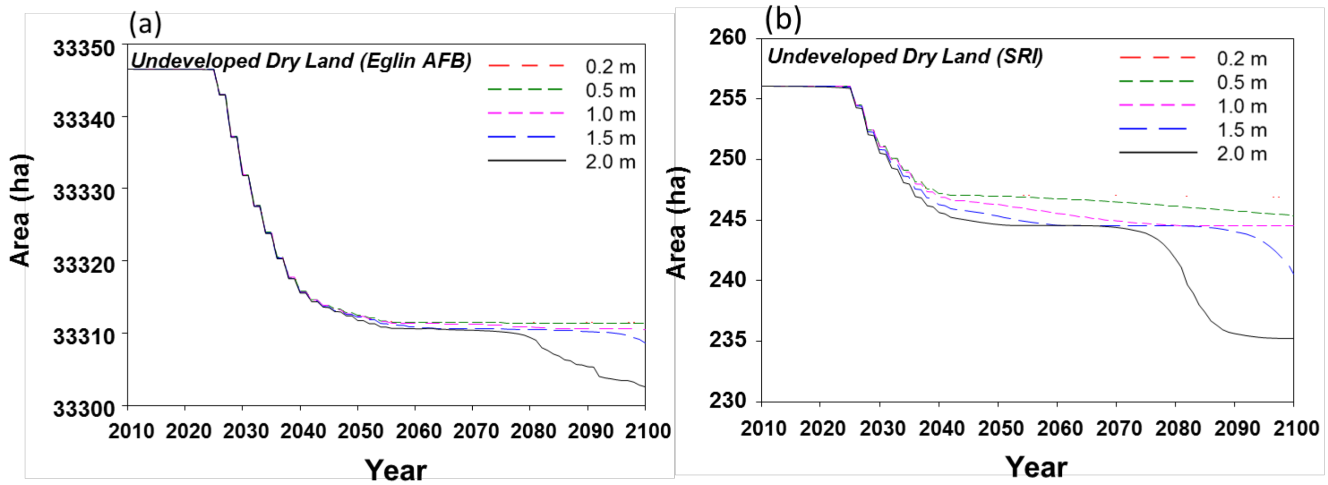


Figure 14. Changes in the area of undeveloped dry land for (a) Eglin AFB and (b) Santa Rosa Island at different SLR rise.

The undeveloped dry land on SRI constitutes 0.8% of the total undeveloped dry land at Eglin AFB. The effects of SLR on this habitat in SLR showed the same pattern to that in Eglin AFB (Figure 14b). The area did not change until mid 2020's after which the area declined by approximately 4% (10 ha) until 2040. The maximum decrease in area of 8% (21 ha) was observed from 2088 towards the end of the century.

Upland/"Cypress Swamp"

Eglin AFB is comprised mostly of what SLAMM classified as non-tidal and Upland "Cypress swamps" (more than 60% of the total area) (see Table 1 for description). During inundation, this upland/swamp (non-tidal) transitions to transitional salt marsh while Cypress swamp transitions to open water. If erosion occurs, they both convert to tidal flat. Since Upland/Cypress swamp dominates this habitat, transition of this habitat to open water is more probable.

The area of swamp considering all SLR projections consistently decreases from 2010 to 2030 by approximately 0.01% (12 ha). From 2030 onwards, higher SLR projections produced a higher decrease in area (Figure 15a). Surprisingly, the swamp in Eglin AFB is more likely to be affected by the different SLR values compared to the other land cover categories. The maximum decrease was observed at SLR = 2.0 m amounting to 0.06% (68 ha).

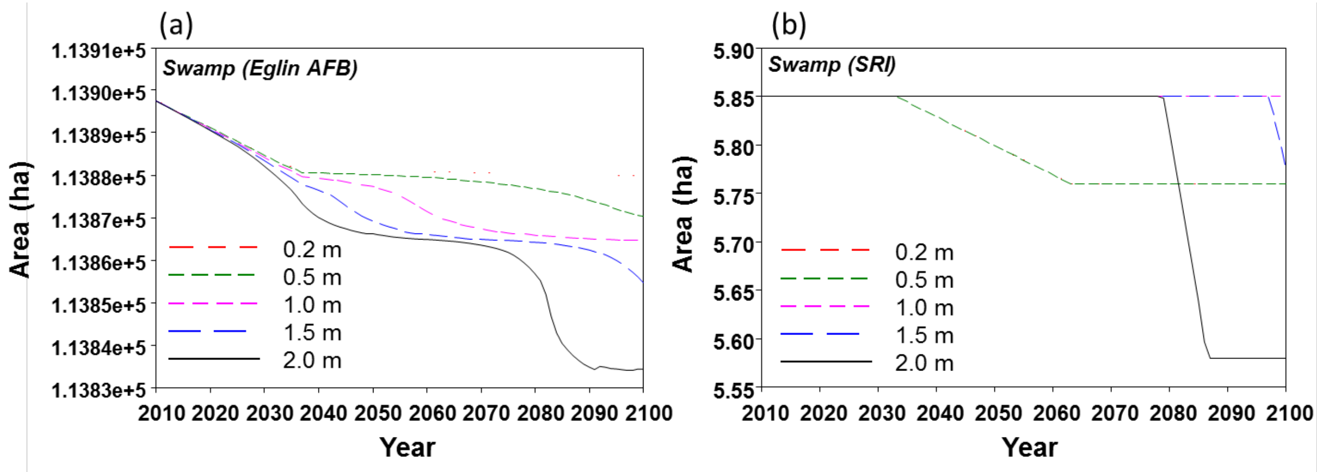


Figure 15. Changes in the area of swamp consisting of non-tidal and cypress swamps for (a) Eglin AFB and (b) Santa Rosa Island at different SLR rise.

The area of swamp on SRI is less than 0.02% (approximately 6 ha) of the total swamp area on Eglin AFB. The effect of the different SLR projections on this habitat on SRI is rather varied. For SLR less than or equal to 0.5 m, the area decreased up to 1.4 % from 2030 to 2060 and hit a plateau after 2060 (Figure 15b). For SLR equal to 1.0 and 1.5 m, no change in the area was observed until the end of the century for SLR = 1.5 m. The reason the swamp land category loses less area (or remains constant) at higher SLR can be due to the fact that at higher SLR, it gained more from the undeveloped dry land which lost more at higher SLR. The maximum decrease in area was at SLR = 2.0 m between 2080 and 2085 which posted a decrease of approximately 5% (0.3 ha). This can imply that despite the gain from undeveloped dry land, swamp also lost to lower elevation habitats.

Marsh

Marsh habitat is composed of inland fresh marsh, transitional salt marsh (scrub shrub), and regularly flooded marsh and constitutes 19% (34,757 ha) of the total area of Eglin AFB. The lower boundary of marshes is the tidal flat and conversion to it is either by inundation or erosion. Once it is converted to tidal flat, it can transition to estuarine open water. The area of the marsh habitat on Eglin AFB consistently decreased from 2010 up to 2030 registering a maximum decrease of 0.17% (59 ha) by 2030 (Figure 16a). From this period forward, the marsh area remained approximately constant for all SLR projections until the end of the century except at SLR = 2.0 m. Around 2080 at SLR = 2.0 m, the area was observed to increase until 2100 which could have been gained from the decrease in swamp within the same time frame (see Figure 15a). However, at the end of the century, there is still a net decrease of 0.15% (52 ha) in the marsh area.

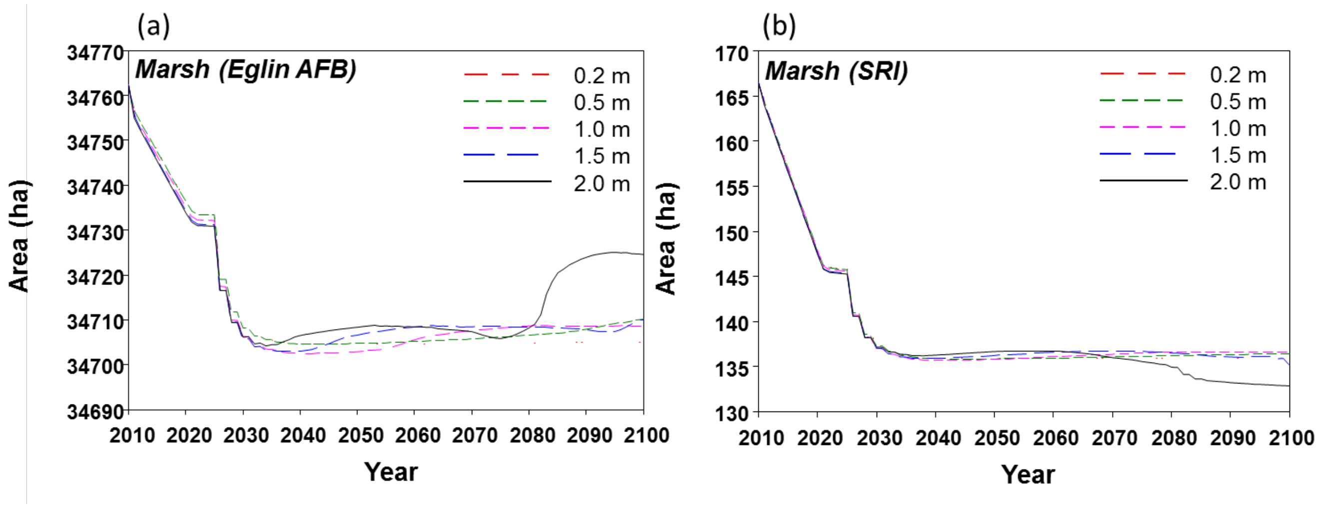


Figure 16. Changes in the area of marshes consisting of inland fresh, transitional salt marsh, and regularly flooded marsh for (a) Eglin AFB and (b) Santa Rosa Island at different SLR rise.

Although SRI has only 0.5% of the marsh area for all of Eglin AFB, it is the most affected category by SLR (Figure 16b). The first 30 years (2010-2030) is the most critical period within which a loss of approximately 18% (30 ha) occurs which is more than 50% of marsh lost for all of Eglin AFB. After 2030, the area remained constant until 2100 except for a slight decrease in 2070 for SLR = 2.0 m. In general, the different SLR projections simulated the same area for the marshes, which implies that the vulnerability of this land cover category in SRI in inevitable regardless of the SLR projection.

Beach

The beach habitat is comprised of the estuarine beach, tidal flat, and ocean beach which occupies 1.4% (2,683 ha) of Eglin AFB. As expected, the beach habitat posted an increase in area gained from the losses in higher elevation habitats (most probably marshes). For the first 30 years (2010-2040), the beach is expected to increase by a maximum amount of 3% (81 ha) (Figure 16a). However, from 2050 forward, the area started to decrease gradually until the end of the century posting a net gain of 2.0% (54 ha). It is surprising to note that the different SLR projections have the same effects on beach habitat (Figure 17 and Figure 18) despite the fact the beach interfaces with ocean.

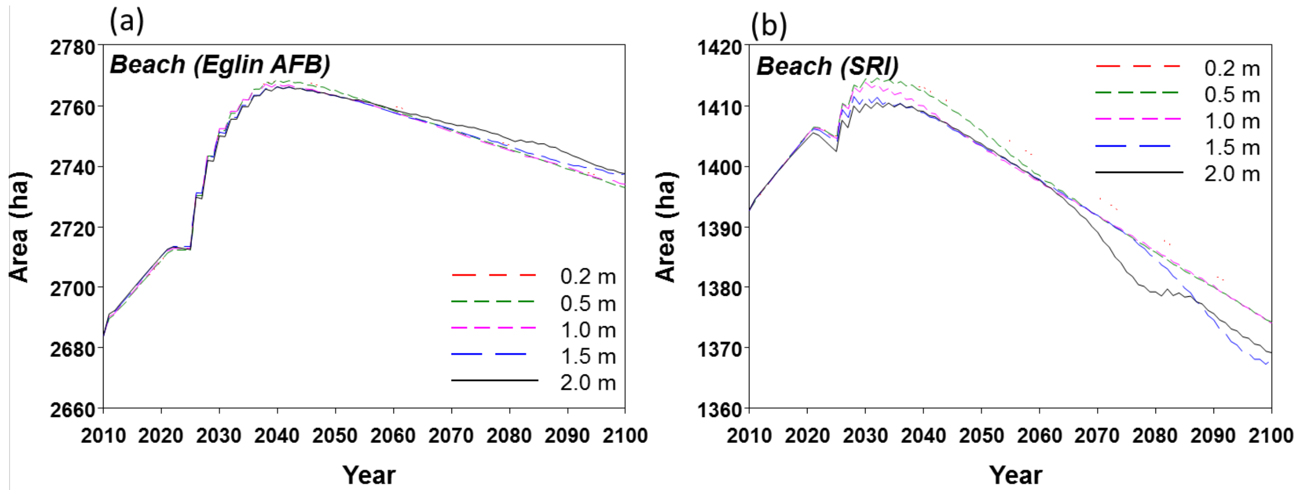


Figure 17. Changes in the area of the beach habitat consisting of estuarine beach, tidal flat, and ocean beach for (a) Eglin AFB and (b) Santa Rosa Island at different SLR rise.

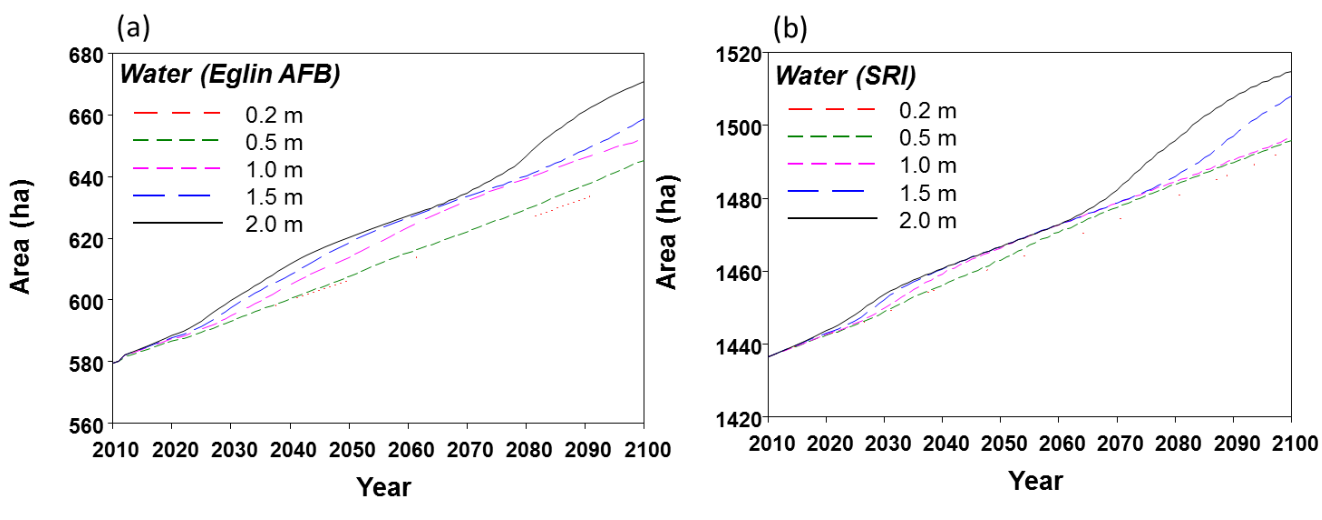


Figure 18. Changes in the area of the water for (a) Eglin AFB and (b) Santa Rosa Island at different SLR rise.

More than 50% of the beach habitat at Eglin AFB is found on SRI. The pattern of the change in area of the beach habitat on SRI is similar to that at Eglin AFB (Figure 17b). However, the rate of decrease in the beach area after 2040 is faster compared to all of Eglin AFB. This resulted in a net loss (instead of a gain) from 2067 onwards with a maximum loss of 1.7% (24 ha) in 2100.

Water

Water on Eglin AFB consists of inland open water, estuarine open water and, open ocean. The simulated area in Eglin AFB contains approximately 580 ha of open water habitat which continuously increased by 16% (93 ha) at the end of the century as more beach habitat converts to open water. The open water habitat on SRI has a bigger area than that of Eglin (1437 ha) and posted a maximum increase equal to 5% (72 ha) by 2100 m. The increase in open water is expected to come from the conversion of beach habitat. However, by 2100 the beach habitat on

Eglin AFB also gained some area (54 ha). Similarly, although SRI lost some 24 ha by 2100, this cannot compensate for the 72-ha gain in open water. This is a typical example of how migration is simulated in the model. While some fraction of the beach habitat transitioned to open water (thus the increase in area of open water habitat), other habitats converted to beach to compensate for the losses. This gives an impression that the beach habitat is migrating inland.

4.4.2 Exposure of Eglin Coast to SLR

The vulnerability of the 74-km stretch of coastline, which includes the coastline of Eglin, was evaluated using SLAMM considering a 120m x 120m resolution. This resolution was used to match the resolution of the whole Gulf Coast of Florida, which will be the basis of comparison in the next section. The total area simulated was 74,288 ha, approximately 48% (35,662 ha) of which is open ocean and the remaining 52% (38,626 ha) consists mostly of land masses. Twenty-nine percent (11,342 ha) of the land mass is undeveloped dry land, 27% (10,510 ha) is swamp, and another 27% (10,593 ha) is cypress swamp. The rest of the area is comprised of varying percentages of marshes and beaches.

The changes in land area were reported for 2010 and 2100 only considering the different SLR projections (i.e., SLR = 0.2, 0.5, 1.0, 1.5, and 2.0 m) and are summarized in Figures 19-22. Each graph has six bars, the first is the area of the category in 2010 and the rest is the area at the end of the century at different SLR projections. Percent changes in the area between 2010 and 2100 are written on each bar.

Undeveloped land and swamps

In general, higher elevation habitats like the undeveloped dry land and swamps are less likely to be affected by SLR and the different projections compared to other habitats closer to the water edge (Figure 19). By 2100, considering a SLR = 2.0 m, the undeveloped dry land decreased by approximately 5.9% (673 ha) and the cypress swamp by 3.2% (342 ha). The swamp on the other hand is expected to increase by 1.3% (141 ha). The categories in this group exhibit a decrease in area as the SLR projection increased except for the swamp which showed a slight increase in area. The increase in the swamp area is expected to come from undeveloped dry land since it is the only category with a higher elevation than swamp. Undeveloped dry land normally converts to transitional salt marsh, ocean beach, estuarine beach, or mangrove (Clough, 2010). However, if the elevation of the undeveloped dry land is below the water table, saturation can occur and the undeveloped dry land converts to the nearest marsh, swamp, or fresh-water type between the dry land and the open ocean. The increase in swamp area is an indication that at SLR greater than or equal to 1.0 m by 2100, when the area starts to increase, the water table will rise higher than the elevation of the undeveloped dry land resulting in saturation.

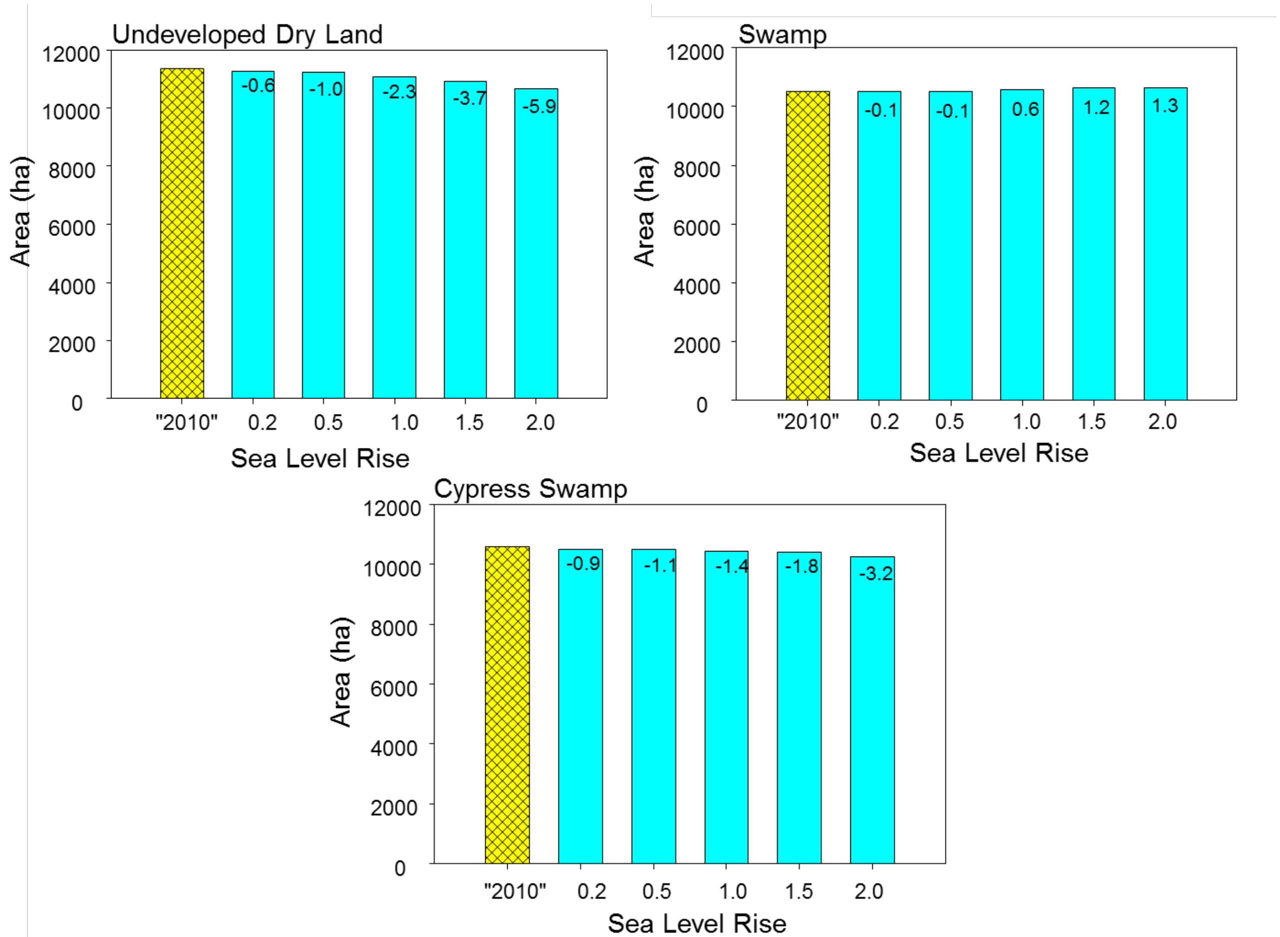


Figure 19. Changes in area in undeveloped dry land and swamps for 2010 and 2100 at different SLR projections for the Eglin coast. Numbers on the bars are the percent change between these two periods. Undeveloped dry land converts to salt marsh, ocean/estuarine beach, or mangrove through inundation. Swamp transitions to transitional salt marsh by inundation and to tidal flat by erosion. Cypress swamp migrates to open water by inundation and to tidal flat by erosion.

Swamp and cypress swamp convert to transitional salt marsh and open water, respectively, by inundation. On the other hand, erosion will convert these categories to tidal flat. This means that for instance, swamp cells computed using equation 3 will become transitional salt marsh while cells computed using equation 4 will become tidal flat.

Marsh

This group is comprised of inland fresh marsh, transitional salt marsh, and regularly flooded marsh. Between 2010 and 2100 at SLR = 2.0 m, the area of inland fresh marsh decreased by 5.7% (8 ha) while the area of the transitional salt marsh increased by 2.5% (39 ha) (Figure 20). The increase in area in the transitional salt marsh can come from undeveloped dry land, and inland fresh marsh. The regularly flooded marsh posted the highest decrease in area, from 22 to 28% (152 to 175 ha), among the marshes. Regularly flooded marsh can transition to tidal flat by inundation and/or erosion.

An increasing SLR projection caused a decrease in the area of inland fresh marsh from 1.3 to 5.7% (loss of 2 to 8 ha in Figure 20). Transitional salt marsh has a varied response to the

different SLR projections. At SLR = 0.2 m, transitional salt marsh lost 2.3% (36 ha) but recovered this loss as SLR rise projection increased. This is because as the SLR projection increased, losses in undeveloped dry land and inland fresh marsh also increased which converted to transitional salt marsh. Although the regularly flooded marsh has the highest decrease in area between 2010 and 2100, it was less affected by the different SLR projections (Figure 20). The loss in area between the different projections was from 22 to 28% (150 to 175 ha) which is minimal considering the area of this category.

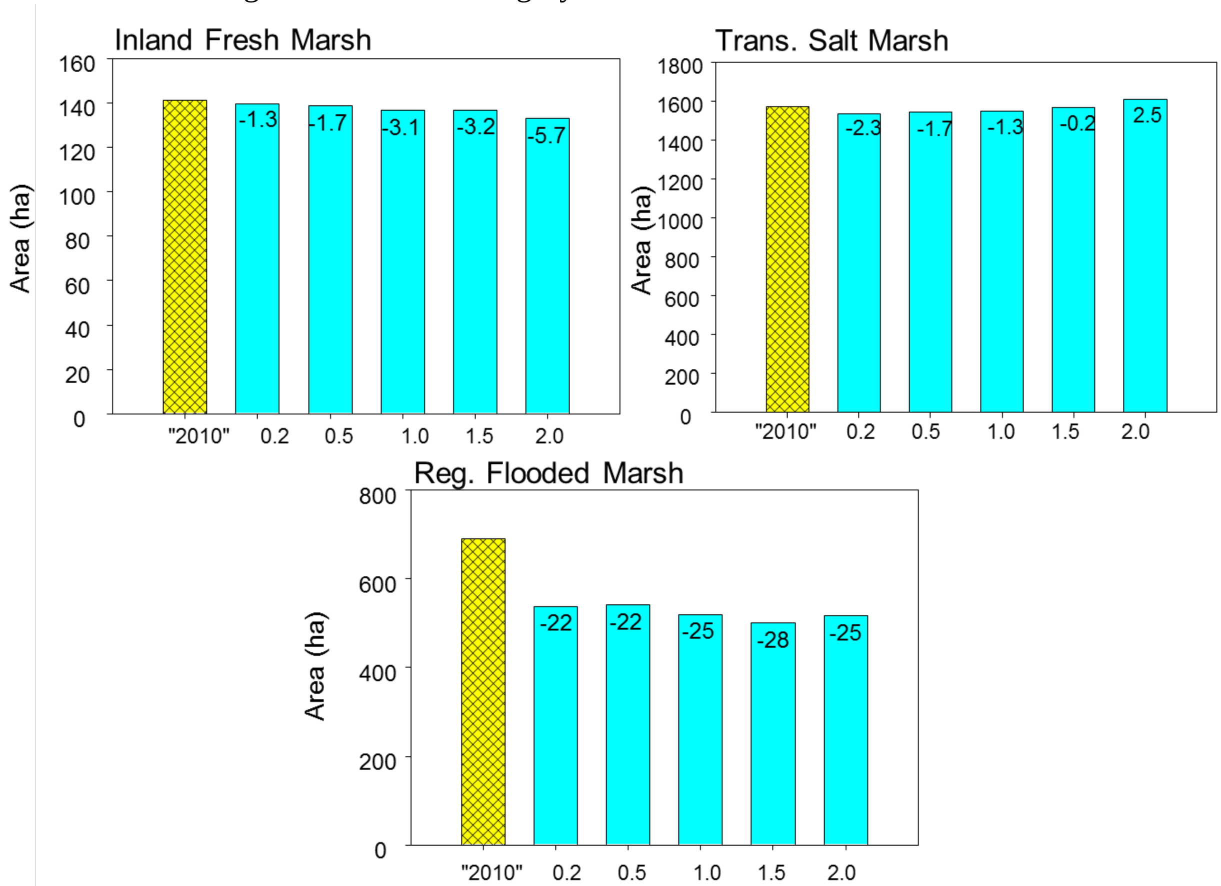


Figure 20. Change in area of marshes for 2010 and 2100 at different SLR projections for the Eglin coast. Numbers on the bars are the percent change between these two periods. Inland fresh marsh and transitional salt marsh transition to regularly flooded marsh by inundation and to tidal flat by erosion. Regularly flooded marsh in turn converts to tidal flat.

Beach

The beach habitat is comprised of the estuarine beach, tidal flat, and ocean beach (Figure 21). Estuarine beach has the highest percentage of area in this habitat. Between 2010 and 2100, a decrease in area of 2.8 to 10.5% (loss of 95 to 352 ha) in estuarine beach is expected which will convert to open water by inundation and/or erosion. The area of the tidal flat is expected to increase by 638 to 659% (166 to 173 ha) by 2100. This is not surprising since swamps and marshes convert to tidal flat when erosion is present. Alternatively, tidal flat can convert to estuarine open water but even if this happens, the loss is compensated by the gain from other categories resulting in a net increase in area. In general, the ocean beach area is expected to

increase by the end of the century. The increase will come from undeveloped dry land adjacent to the water. Estuarine beach and ocean beach convert to estuarine open water.

The effects of the different SLR projection on the beach habitat were varied. The area of the estuarine beach decreased as the SLR projection increased. The effects of the different SLR projections on the area of tidal flat was quite minimal (from 166 to 173 ha), but rather variable on the area of ocean beach (from an increase of 8.3% to a decrease of 3.9%) (Figure 21). This variability can play an important role in the outcome of beach habitat. For example, at SLR = 2.0 m, the estuarine beach will lose 10.5% (352 ha) while the tidal flat and ocean beach will gain 646% and 3.1% (173 and 12 ha), respectively. This shows that approximately 5% (171 ha) of beach habitat will be "lost" (i.e., converted to open water) if SLR reaches 2.0 m by 2100. However, if SLR reaches only 1.0 m by 2100, the estuarine beach will decrease by 3.2% (107 ha) while tidal flat and ocean beach will increase by 640% and 8.3% (166 ha and 32 ha), respectively, resulting in a net gain of approximately 2.4% (91 ha) in beach habitat. Therefore, a decrease in the area of beach habitat is expected only if sea level rises beyond 1.0 m by 2100. This is an important consideration since beach habitat is critically important for a multitude of protected plants and animals. Protection and conservation of these habitats will depend on these possible outcomes.

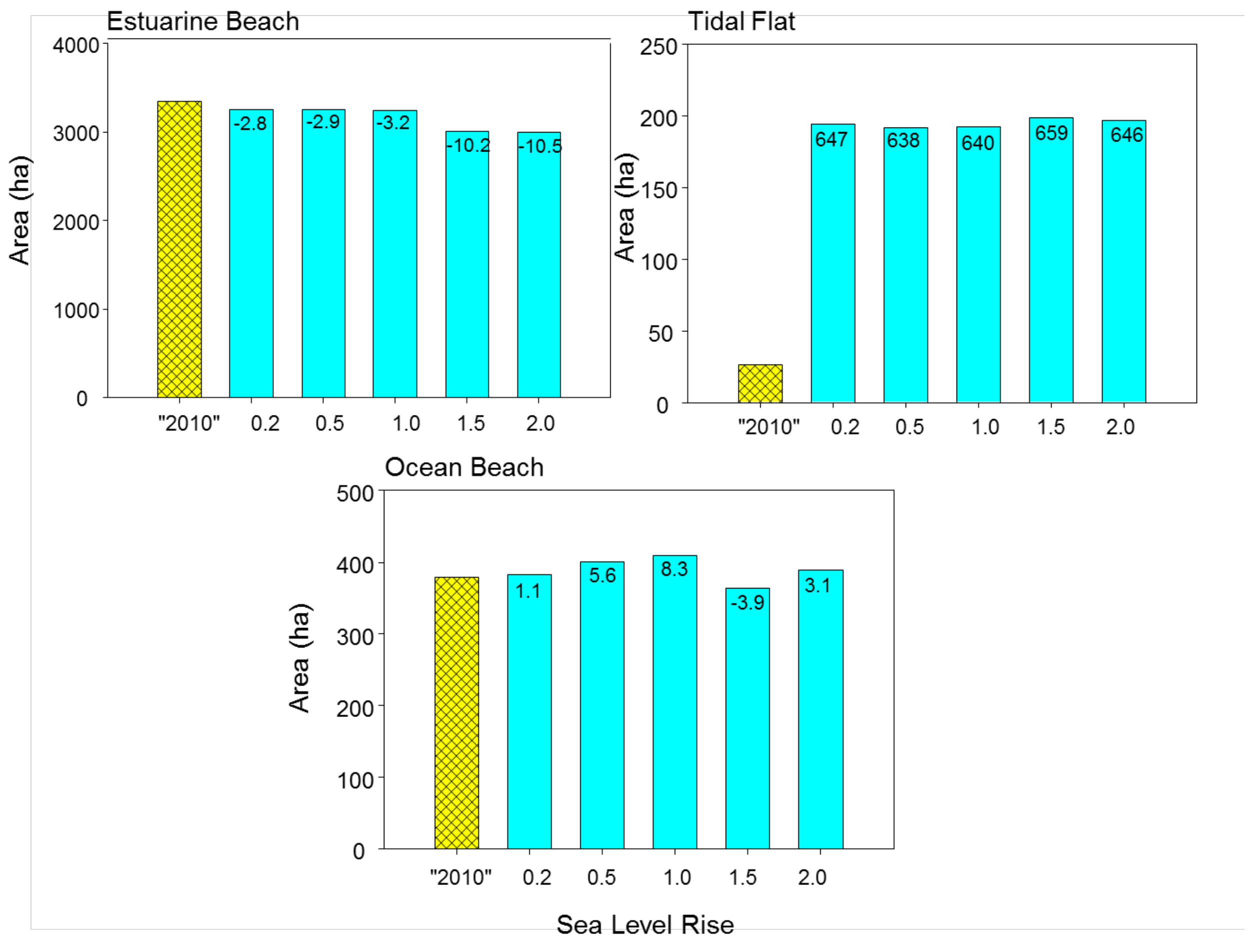


Figure 21. Changes in area in the beach habitat for 2010 and 2100 at different SLR projections

for Eglin Coast. Numbers on the bars are the percent change between these two periods. The beach habitat converts to either estuarine open water or open ocean.

Water

Open water includes inland open water, estuarine open water, and open ocean. As expected, the area of open water increased between 2010 and 2100 except for inland open water, which remained constant (Figure 22). However, the contribution of inland open water is negligible since it occupies a very small percentage of the entire study area. Estuarine open water has the highest increase in area between 2010 and 2100. It is also the most affected category by SLR projections with an increase in area of 296% (54 ha) at SLR = 0.2 m to 2808% (557 ha) at SLR = 2.0 m. The increase in area in this category can be attributed from the losses in mangrove and tidal flat. However, since the mangrove posted a maximum loss of only 1 ha, the most probable source of the increase in area of estuarine open water is from conversion of tidal flat. However, the area of tidal flat is expected to increase at the end of the century. This means that tidal flat has to gain sufficient area (more than 500 ha) from conversion of swamps and marshes to lose it to estuarine open water (see Figure 22). This is a confirmation of the earlier assessment that the loss in tidal flat area is overly compensated by the gain from swamps and marshes, as indicated by the increase area, which suggests that the tidal flat has underwent considerable inland migration.

Overall, there is an increase in the area of open water (estuarine open water and open ocean), which will favor estuarine organisms but may have drastic effects on terrestrial and shoreline-dependent organisms.

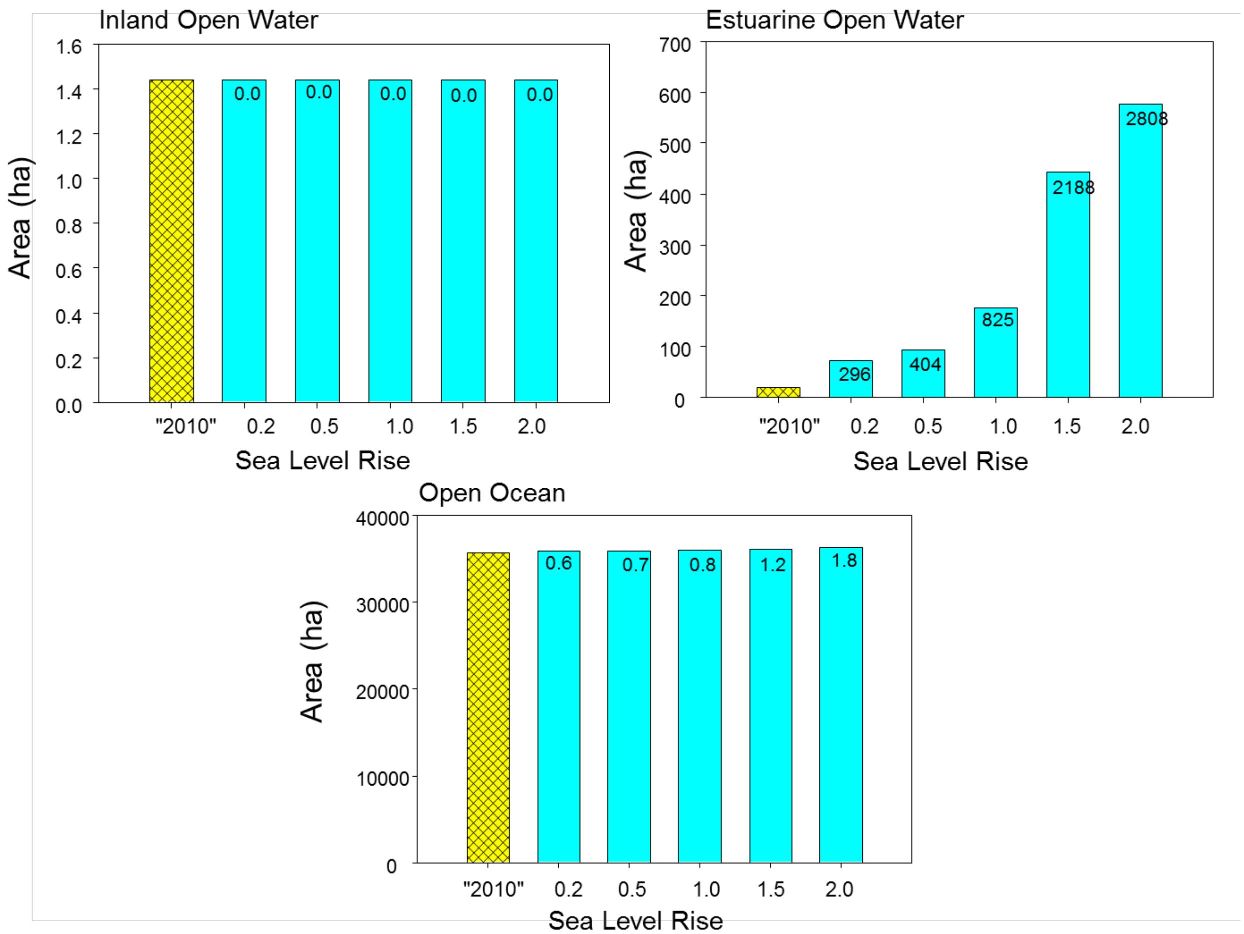


Figure 22. Changes in the area of open water for 2010 and 2100 at different SLR projections for the Eglin Coast. Numbers on the bars are the percent change between these two periods.

4.4.3 Comparison with Tyndall and the Gulf Coast of Florida

The land cover of the Tyndall AFB coastline (Figure 23b) and the whole Gulf Coast of Florida (Figure 23a) were also simulated using SLAMM at different SLR projections (0.2 m, 0.5 m, 1.0 m, 1.5 m, and 2.0 m). For both regions, a 10km distance inland was investigated. The changes in area of the land cover categories between 2010 and 2100 at SLR = 2.0 m at Eglin AFB were then compared with those of Tyndall AFB and the Florida Gulf Coast (Figures 24-27). Comparisons were made among the four groups of habitats previously investigated. In Figures 24-27, the percentage of the land mass in each region (i.e., Eglin, Tyndall, and FL) for 2010 (the left bar) was compared to those of 2100 (right bar) at SLR = 2.0 m.

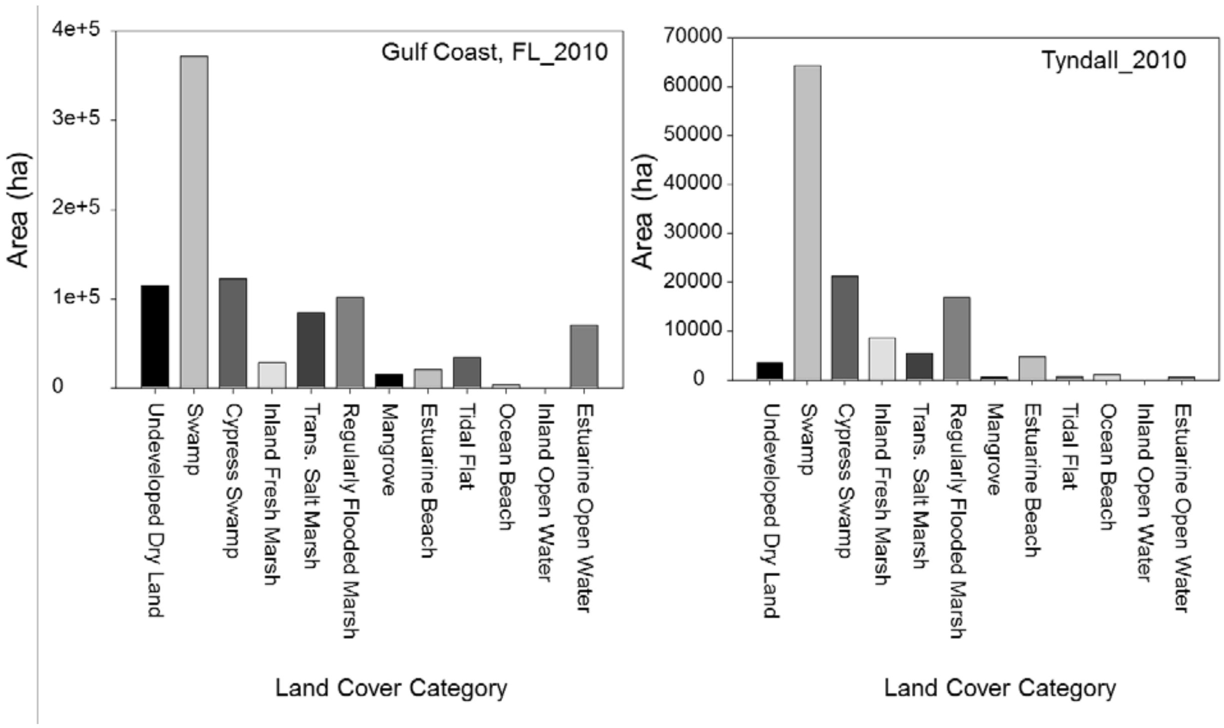


Figure 23. Land cover of (a) the Gulf Coast of Florida and (b) Tyndall AFB at 120 m x 120 m resolution. The Gulf Coast of Florida has a simulated area of 1.6M ha while Tyndall AFB has a simulated area of 248,952 ha. Approximately 40% of the former and 48% of the latter is open ocean.

Undeveloped dry land and swamp habitats

The higher elevation wetlands of Eglin are in general more stable compared to those at Tyndall and of the Florida Gulf Coast (Figure 24). The undeveloped dry area only decreased by 6% as compared to the 39 and 32% decrease in Tyndall and the Gulf Coast of Florida, respectively. The swamp category at Eglin is the only one among the three regions which manifested an increase in area (1%) while Tyndall and Florida decreased by more than 40%. This is an indication that saturation (rising of water table to the surface) is more dominant at Eglin than the other two regions. An increase in swamp area can be caused by saturation of undeveloped dry land which results in conversion to swamp. Cypress swamp in the three regions decreased but the decrease at Eglin is minimal compared to that on Tyndall or along the remainder of the Gulf Coast.

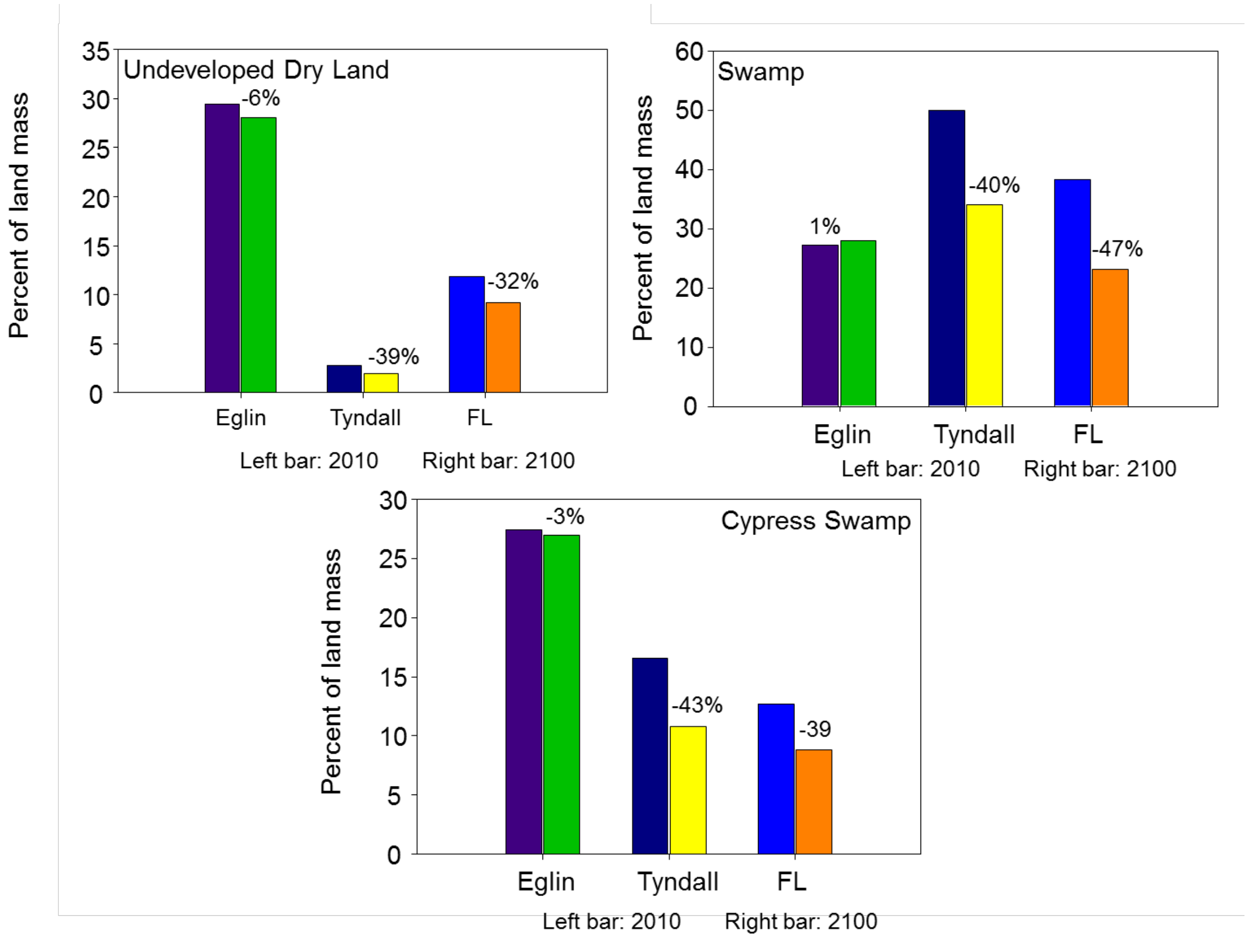


Figure 24. Comparison of the changes in higher elevation wetlands for Eglin, Tyndall, and the Gulf Coast of Florida between 2010 and 2100 at SLR = 2.0 m. Numbers on top of the bars represent the percent change in area between these two periods.

Marsh habitats

The marshes at Eglin manifested lesser change compared to at Tyndall or along the broader Gulf Coast (Figure 25). Inland fresh marsh decreased by only 6% as compared to a 31% decrease at Tyndall and a 47% decrease along the Gulf Coast. The transitional salt marsh at Tyndall had a large increase (195%) in area in 2100 compared to Eglin (2%) while the whole Gulf Coast experienced a 15% decrease in transitional salt marsh. An opposite trend in the fate of the transitional marsh was observed in regularly flooded marsh. Eglin and Tyndall decreased by 25 and 86%, respectively, while the Gulf Coast increased by 66%.

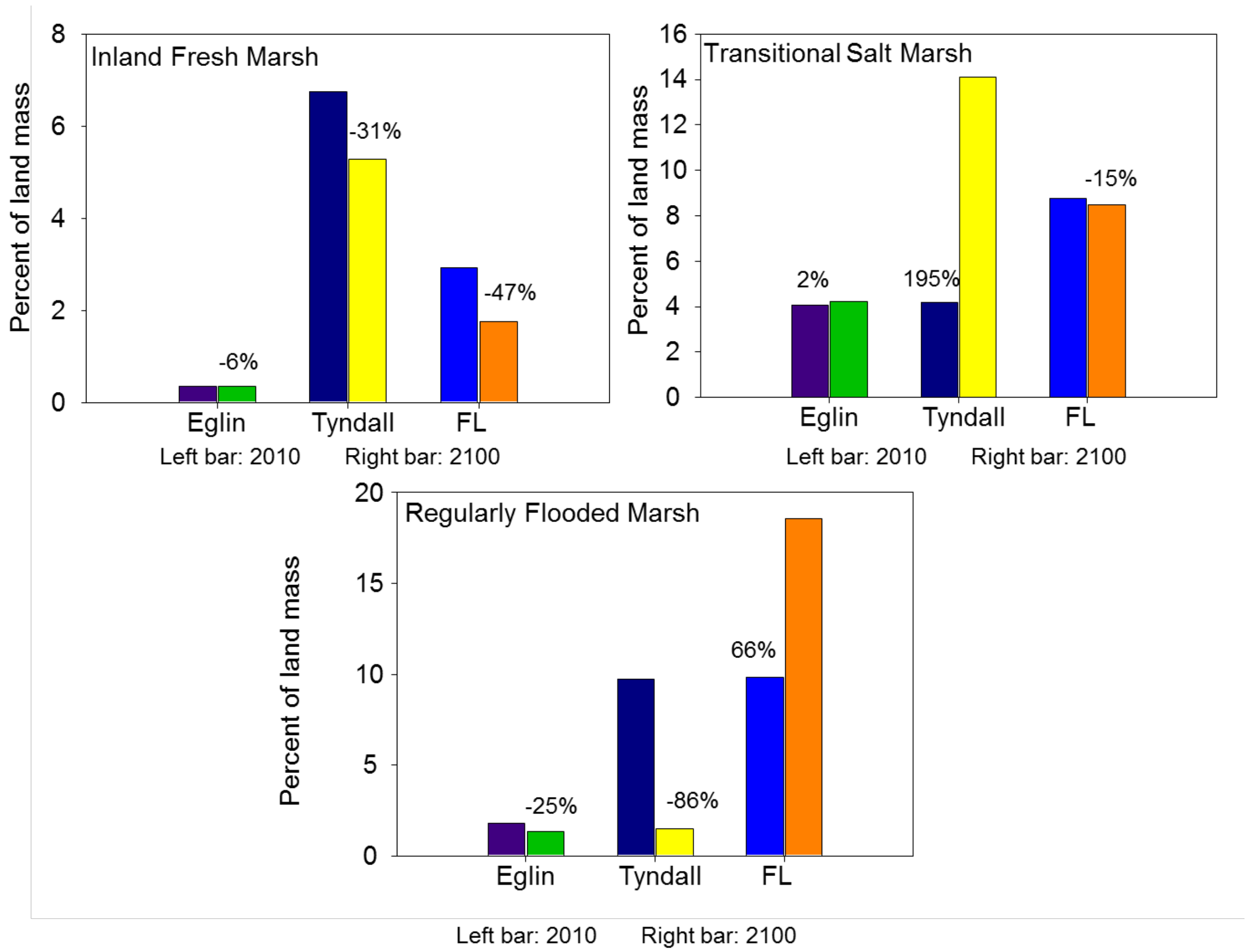


Figure 25. Comparison of the changes in marshes and mangrove for Eglin, Tyndall, and the Gulf Coast of Florida between 2010 and 2100 at SLR = 2.0 m. Numbers on top of the bars represent the percent change in area between these two periods.

Beach habitats

Eglin showed the smallest change in estuarine beach and ocean beach habitats but showed the highest change in tidal flat compared to the other two regions (Figure 26). Not only did tidal flat show the highest change, it posted an increase in area of 646% while Tyndall and the Gulf Coast showed a decrease of 85 and 21%, respectively. At Tyndall and along the remaining Gulf Coast, loss in tidal flat can be an indication that more tidal flat area converts to estuarine open water compared to the area of swamps and marshes undergoing erosion. Erosion of swamps and marshes resulted in conversion to tidal flat. This higher increase in tidal flat area at Eglin suggests this habitat is more dynamic at Eglin than at Tyndall or along the remaining Gulf Coast, the latter two of which experience frequent tidal flat migration during the next 100 years.

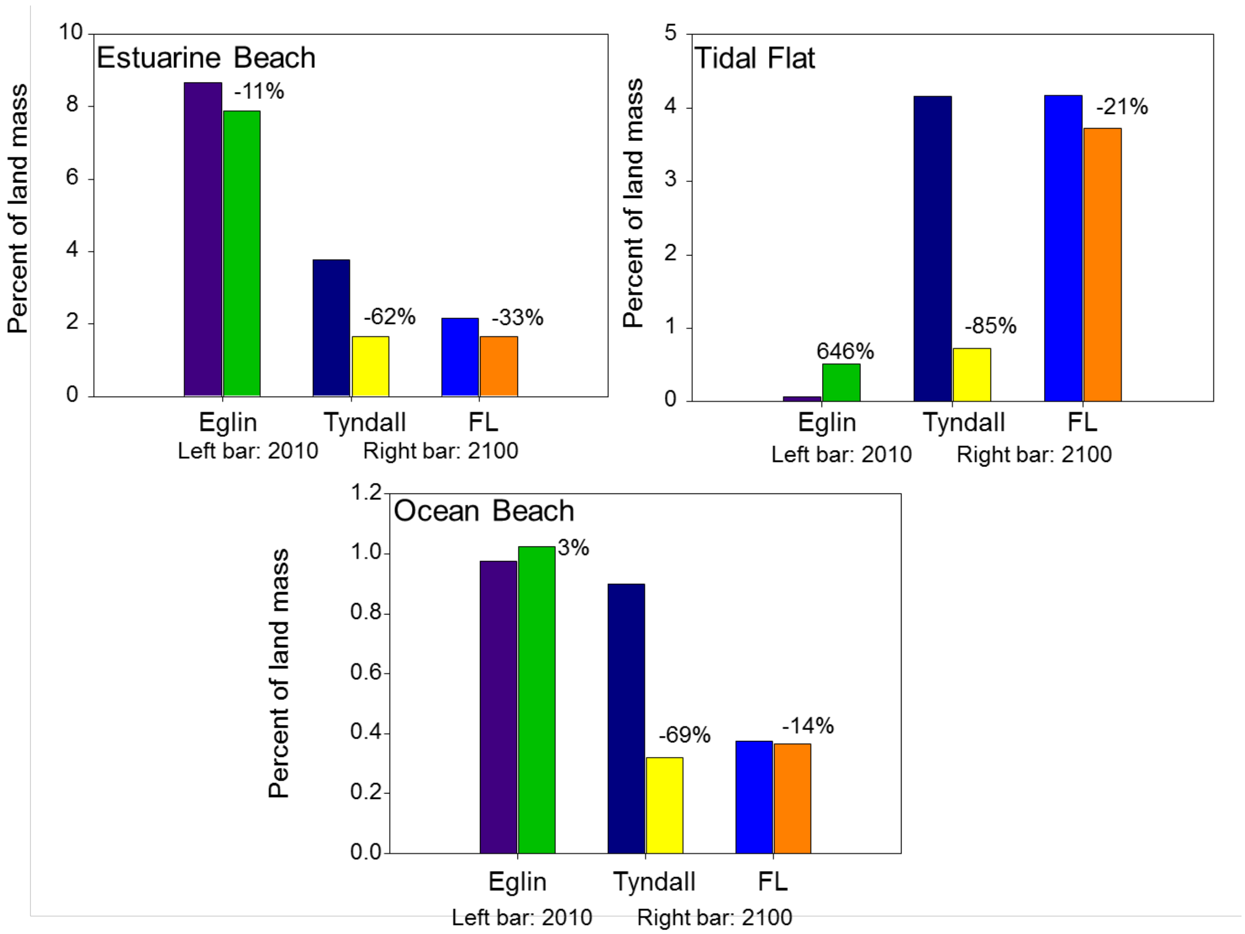


Figure 26. Comparison of the changes in the beach habitat for Eglin, Tyndall, and the Gulf Coast of Florida between 2010 and 2100 at SLR = 2.0 m. Numbers on top of the bars represent the percent change in area between these two periods.

Open water habitats

There is a general increase in open water area at Eglin, Tyndall, and along the Gulf Coast in general. Although inland open water posted an increase in area, it occupies a very small percentage of the total area to make any significant contribution (Figure 27). The estuarine open water at Tyndall showed the highest increase of 4099%, followed by Eglin with a 2808% increase, and then by the remaining Gulf Coast with 192% increase. This broad-scale increase in all regions comes from the decrease in area of tidal flats since this habitat converts directly to estuarine open water, which is clearly demonstrated in our simulations at Tyndall and along the remaining Gulf Coast However, at Eglin AFB, the conversion of tidal flat to estuarine open water was compensated by the gains from mangrove and undeveloped dry land.

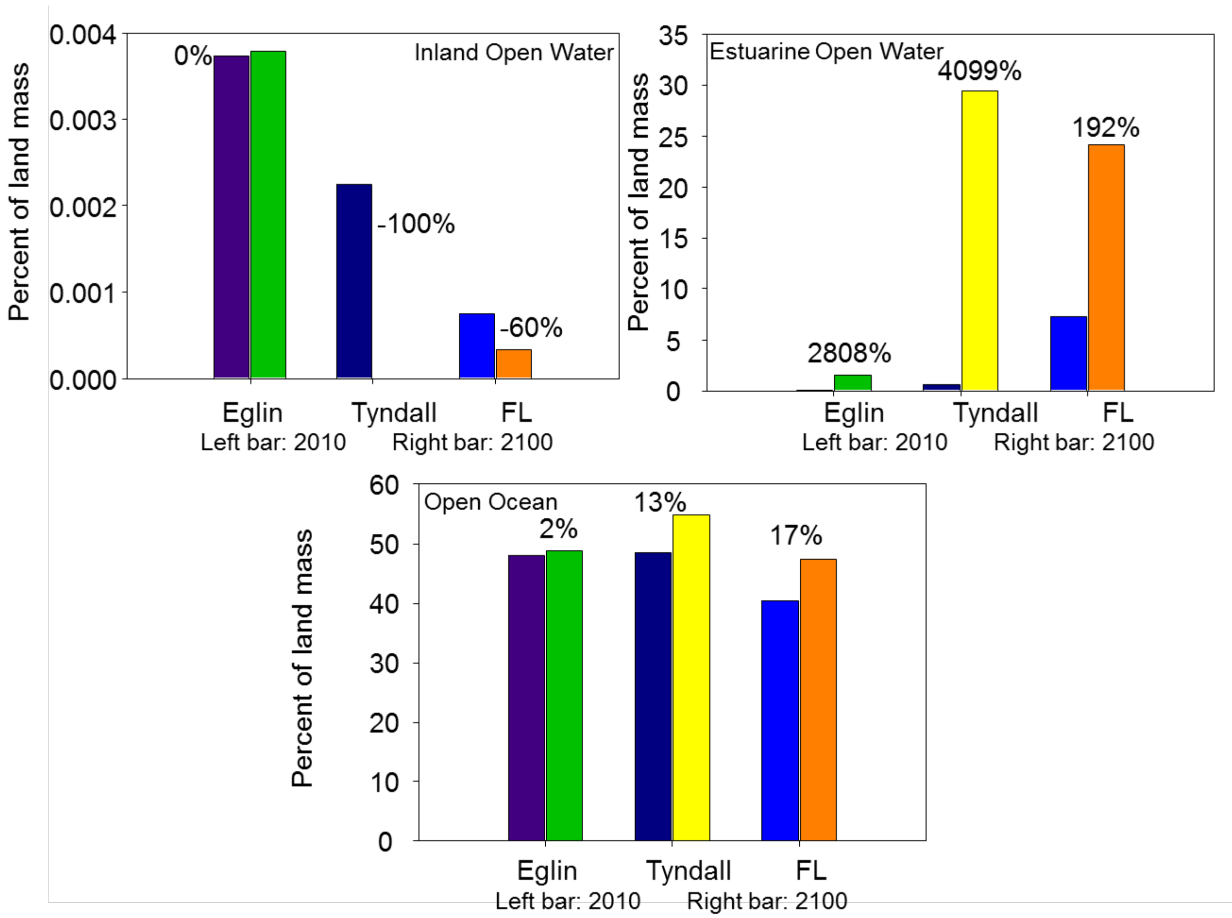


Figure 27. Comparison of the changes in open water for Eglin, Tyndall, and the Gulf Coast of Florida between 2010 and 2100 at SLR = 2.0 m. Numbers on top of the bars represent the percent change in area between these two periods.

4.5 Decision analysis

4.5.1 MCDA at the Florida Gulf Coast scale

Results of the MCDA are presented as four separate, comparable models: 1m SLR with ceiling density dependence, 1m SLR with contest density dependence, 2m SLR with ceiling density dependence, and 2m SLR with contest density dependence. Uncertainty is represented through the use of these four model scenarios as well as in the values for the measures, which is propagated to the decision goal. Figure 28a-d shows results of the Logical Decisions MCDA analysis under the Coastal Protection Goal where each measure was weighted equally. Using this figure, the management decisions can be ranked. Under the ceiling type density dependence for both 1 and 2 m SLR by 2100 the ranking of management alternatives from best to worst is (1) Exclosures, (2) Predator Management, (3) Beach Nourishment, and (4) No Action. Under the contest type density dependence for both 1 and 2 m SLR by 2100 the ranking of management alternatives from best to worst is (1) Beach Nourishment, (2) No Action, (3) Exclosures, and (4) Predator Management. In all of the model scenarios Exclosures ranks higher than Predator Management because of the weighting measurements used for the Public Popularity measure. The uncertainty within the measures is shown in the results as the standard deviation of the

model run. The uncertainty in each of the scenarios and in each of the management alternatives makes a definitive selection of an optimal alternative unclear.

Figure 29a-d shows results of the Logical Decisions MCDA analysis under the Snowy Plover Protection Goal where each measure was weighted equally. Using this figure, the management decisions can also be ranked solely with respect to species protection without regard to other criteria such as cost. Under the ceiling type density dependence for 1 m SLR by 2100 the ranking of management alternatives from best to worst is (1) Predator Management, (2) Exclosures, (3) Beach Nourishment, and (4) No Action. Here, Predator Management and Exclosures are virtually tied for the first rank. Under the ceiling type density dependence for 2 m SLR by 2100 the ranking of management alternatives from best to worst is (1) Beach Nourishment, (2) Predator Management, (3) Exclosures, and (4) No Action. Here, Predator Management and Exclosures are virtually tied for the first rank. Under the contest type density dependence for 1 m SLR by 2100 the ranking of management alternatives from best to worst is (1) Nourishment, (2) No Action tied with Exclosures and Predator Management. Under the contest type density dependence for 2 m SLR by 2100 the ranking of management alternatives from best to worst is (1) Beach Nourishment, (2) No Action, (3) Exclosures, and (4) Predator Management. The uncertainty within the measures is shown in the results as the standard deviation of the model run. The uncertainty in each of the scenarios and in each of the management alternatives makes a definitive selection of an optimal alternative unclear.

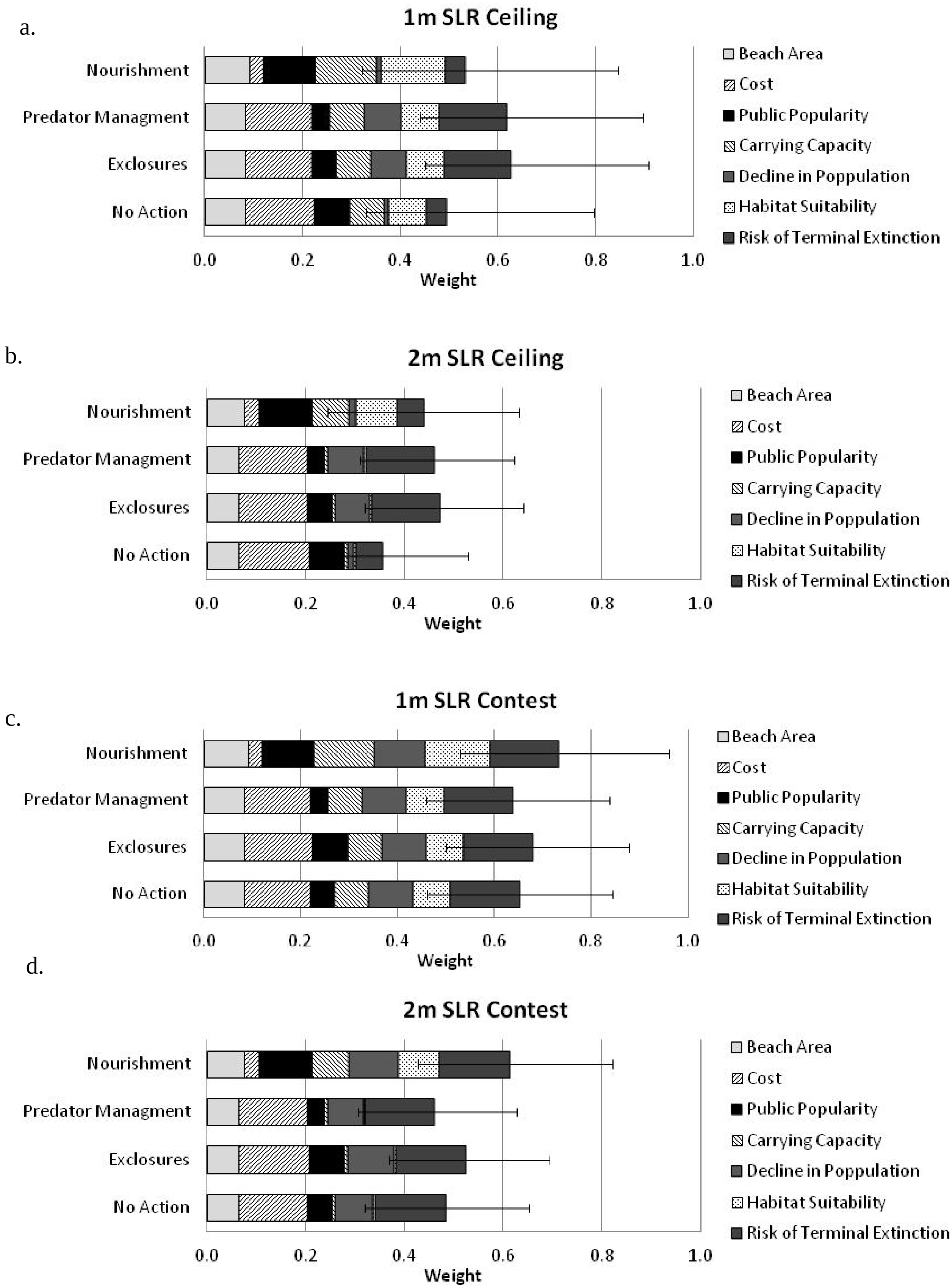
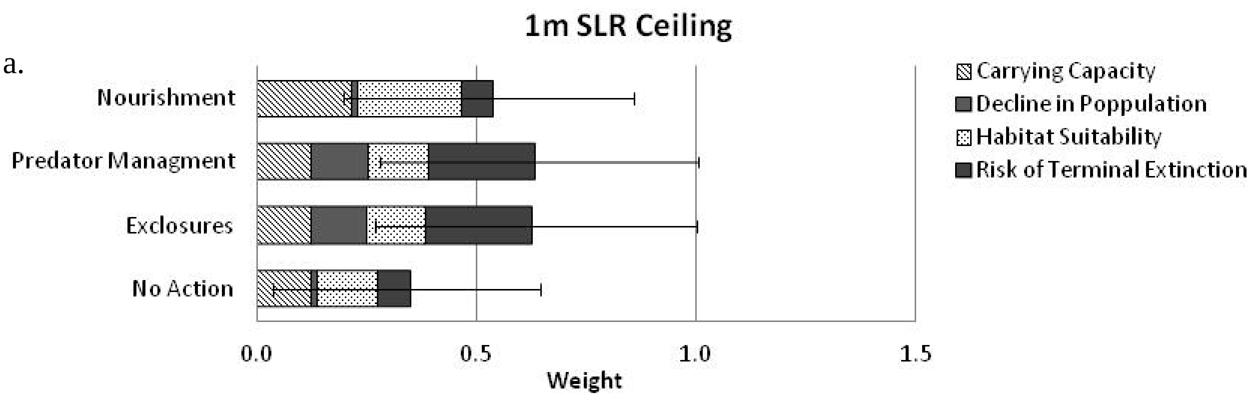
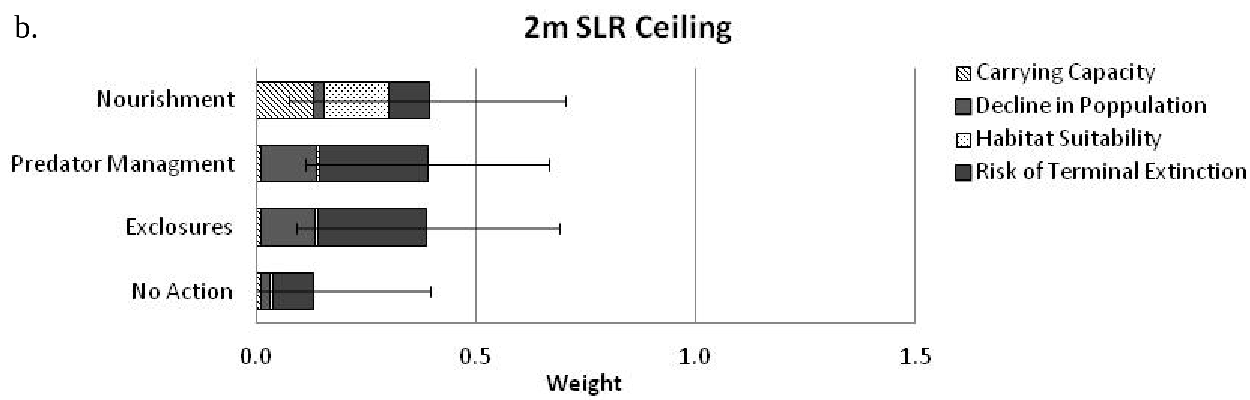

a.
1m SLR Ceiling
Nourishment
Predator Managment
Exclosures
No Action
0.0
0.2
0.4
0.6
0.8
1.0
Weight
Beach Area
Cost
Public Popularity
Carrying Capacity
Decline in Poppulation
Habitat Suitability
Risk of Terminal Extinction
b.
2m SLR Ceiling
Nourishment
Predator Managment
Exclosures
No Action
0.0
0.2
0.4
0.6
0.8
1.0
Weight
Beach Area
Cost
Public Popularity
Carrying Capacity
Decline in Poppulation
Habitat Suitability
Risk of Terminal Extinction
c.
1m SLR Contest
Nourishment
Predator Managment
Exclosures
No Action
0.0
0.2
0.4
0.6
0.8
1.0
Weight
Beach Area
Cost
Public Popularity
Carrying Capacity
Decline in Poppulation
Habitat Suitability
Risk of Terminal Extinction
d.
2m SLR Contest
Nourishment
Predator Managment
Exclosures
No Action
0.0
0.2
0.4
0.6
0.8
1.0
Weight
Beach Area
Cost
Public Popularity
Carrying Capacity
Decline in Poppulation
Habitat Suitability
Risk of Terminal Extinction

Figure 28. Comparison of MCDA Coastal Protection Goal results under (a) 1m SLR by 2100 and ceiling type density dependence, (b) 1m SLR by 2100 and contest type density dependence, (c) 2m SLR by 2100 and ceiling type density dependence, (d) 2m SLR by 2100 and contest type density dependence. Error bars show the 95% Confidence Interval.

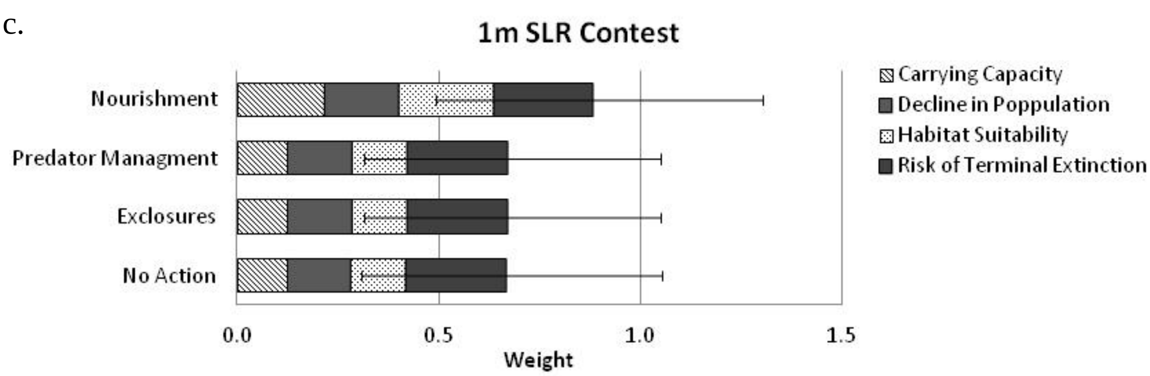
a.



b.



c.



d.

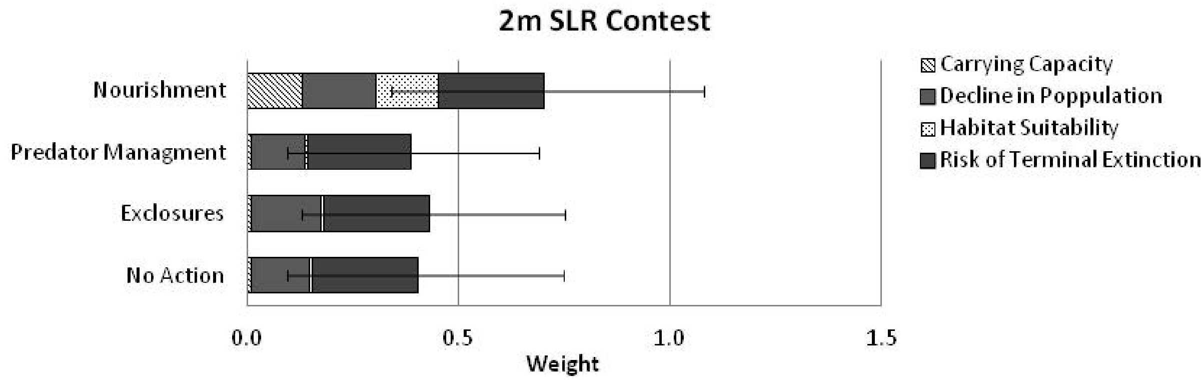


Figure 29. Comparison of MCDA Snowy Plover Protection Goal results under (a) 1m SLR by 2100 and ceiling type density dependence, (b) 1m SLR by 2100 and contest type density dependence, (c) 2m SLR by 2100 and ceiling type density dependence, (d) 2m SLR by 2100 and contest type density dependence. Error bars show the 95% Confidence Interval.

Tables 9 and 10 show quantitative summaries of the Logical Decisions MCDA. These tables, categorized by goal, show the utilities and rankings of each alternative under each scenario. The ranking for each goal is calculated by summing all of the scenarios for 1 and 2 m SLR as well as contest and ceiling type density dependencies. For both the Coastal Protection and Snowy Plover Protection goals, Nourishment ranks as the most preferred alternative and No Action ranks as the least preferred alternative.

Table 9. Alternative Utilities for the Coastal Protection Goal.

Alternative	1m ceiling	2m ceiling	1m contest	2m contest	sum	rank
No Action	0.498	0.357	0.681	0.526	2.062	4
Exclosures	0.630	0.474	0.653	0.484	2.240	2
Predator Management	0.620	0.468	0.639	0.460	2.188	3
SP Beach Nourishment	0.536	0.441	0.732	0.613	2.321	1

Table 10. Alternative Utilities for the Snowy Plover Protection Goal.

Alternative	1m ceiling	2m ceiling	1m contest	2m contest	sum	rank
No Action	0.351	0.135	0.671	0.431	1.587	4
Exclosures	0.629	0.386	0.669	0.403	2.087	3
Predator Management	0.637	0.401	0.671	0.388	2.096	2
SP Beach Nourishment	0.539	0.397	0.881	0.700	2.517	1

Alternative weighting simulations were also run in Logical Decisions where (1) the cost measure was weighted as 50% of the overall Coastal Protection goal (Figure 30) and (2) the risk of extinction measure was weighted as 50% of the overall Coastal Protection goal (Figure 31). Under the highly weighed cost simulation, the nourishment alternative is seen to decrease in utility, ranging from 0.343 to 0.58 in the various scenarios. This can be compared to the other alternatives which range from 0.460 to 0.813 in the various scenarios. Under the highly weighted risk of extinction simulation, there is a range of rankings displayed between the

scenarios with both exclosures and nourishment ranking as the preferred alternative and both no action and predator managed ranking as the least preferred alternative.

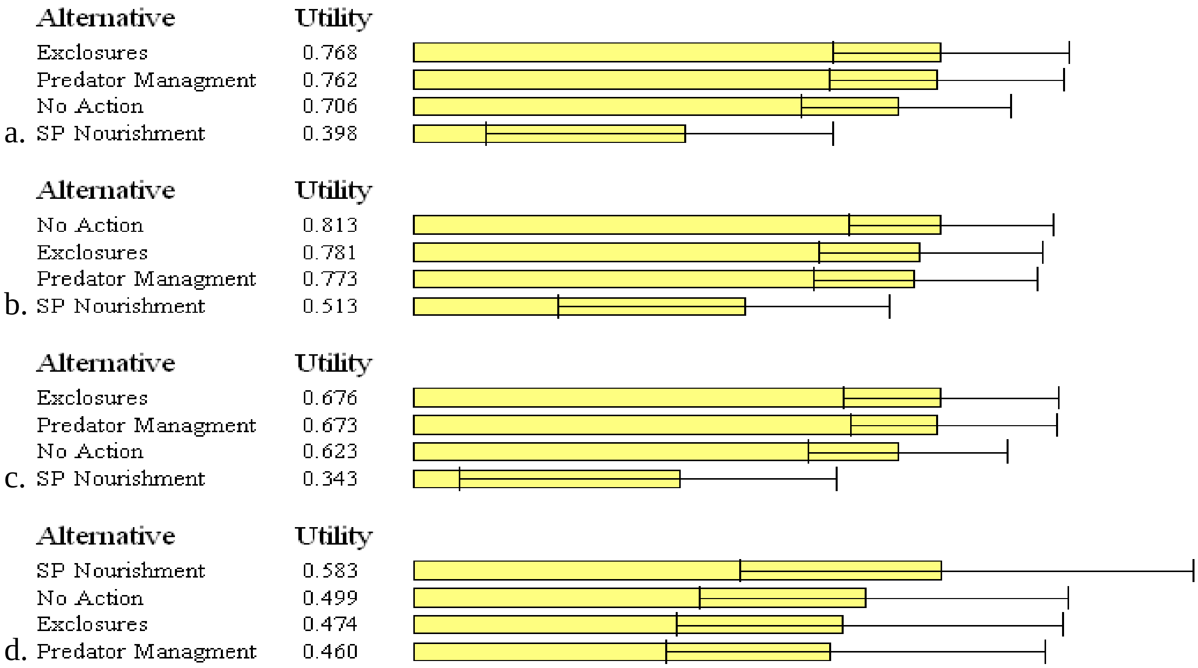


Figure 30. Comparison of Logical Decisions MCDA with cost weighted as 50% of the Coastal Protection Goal results under (a) 1m SLR by 2100 and ceiling type density dependence, (b) 1m SLR by 2100 and contest type density dependence, (c) 2m SLR by 2100 and ceiling type density dependence, (d) 2m SLR by 2100 and contest type density dependence. Error bars show the 95% Confidence Interval.

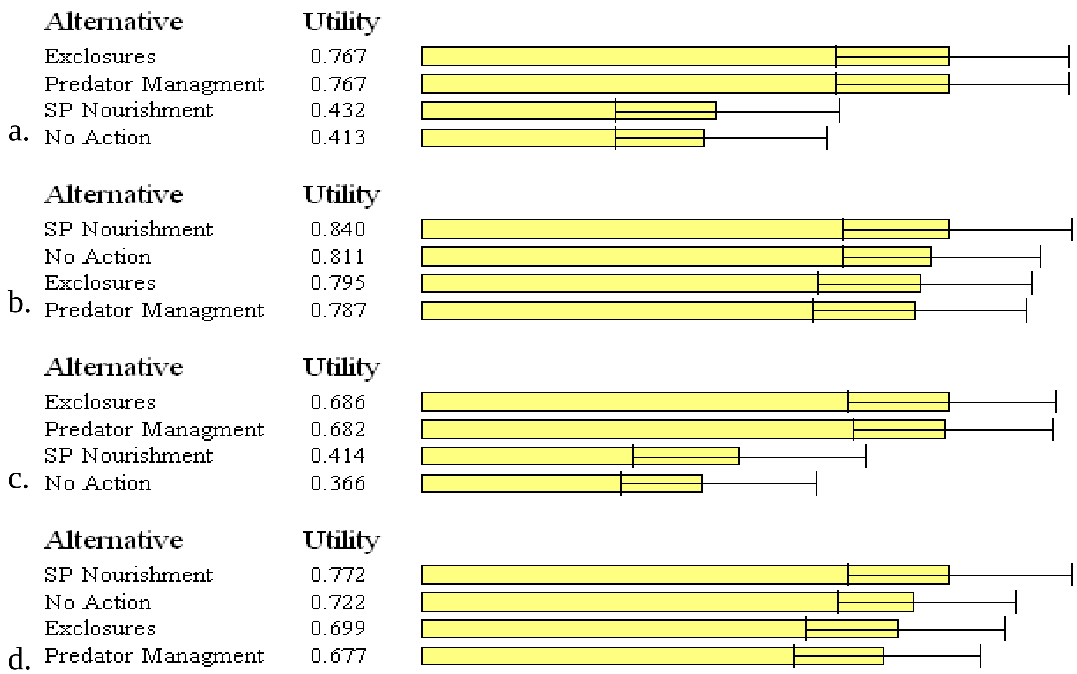
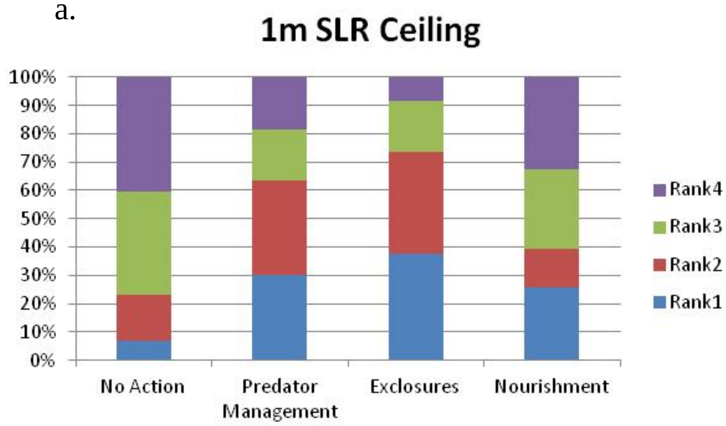


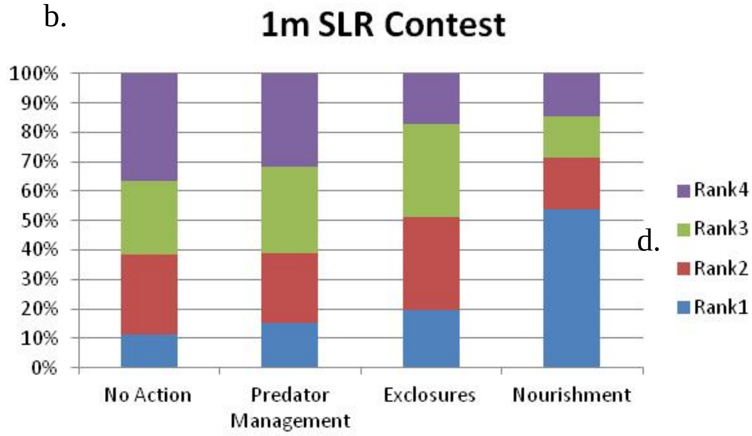
Figure 31. Comparison of Logical Decisions MCDA with risk of extinction weighted as 50% of the Coastal Protection Goal results under (a) 1m SLR by 2100 and ceiling type density dependence, (b) 1m SLR by 2100 and contest type density dependence, (c) 2m SLR by 2100 and ceiling type density dependence, (d) 2m SLR by 2100 and contest type density dependence. Error bars show the 95% Confidence Interval.

JSMAA results are presented in Figure 32. This figure shows the percentage of time that each alternative ranks 1st, 2nd, 3rd, and 4th according to the uncertainty in the measures and various weighting schemes. As with the Logical Decisions results, these results show that nourishment and exclosure alternatives rank as the preferred alternative more frequently than no action or predator management. Additionally, no action ranks last in all but one of the scenarios (2m SLR Contest).

a.

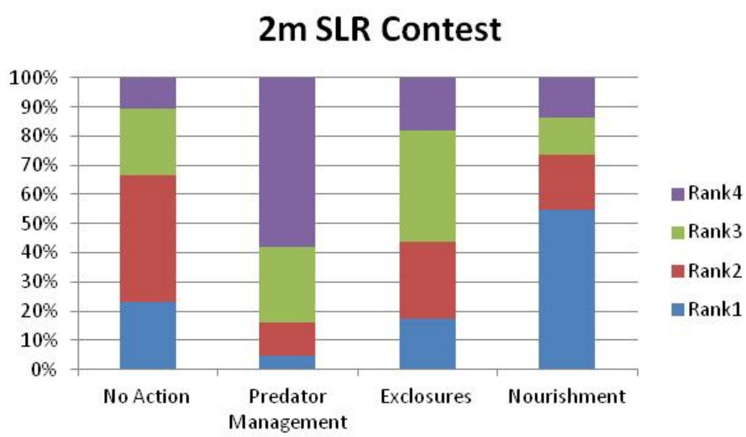

1m SLR Ceiling
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
No Action
Predator Management
Exclosures
Nourishment
Rank4
Rank3
Rank2
Rank1

b.


1m SLR Contest
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
No Action
Predator Management
Exclosures
Nourishment
Rank4
Rank3
Rank2
Rank1

d.

c.


2m SLR Contest
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
No Action
Predator Management
Exclosures
Nourishment
Rank4
Rank3
Rank2
Rank1

d.

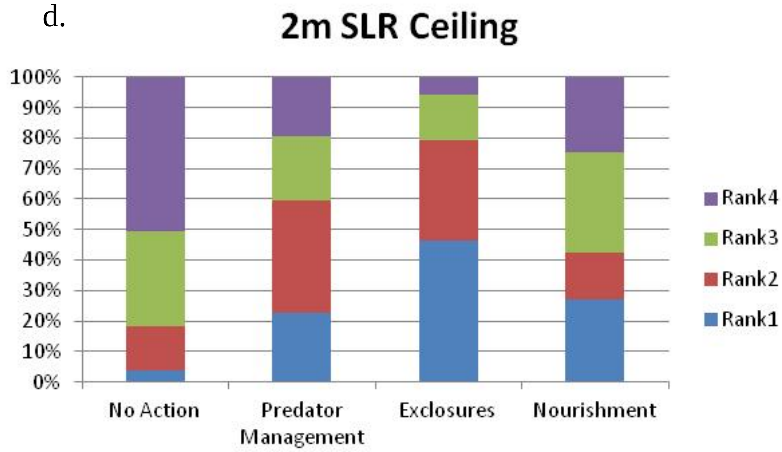


Figure 32. Comparison of JSMAA MCDA Coastal Protection Goal results under (a) 1m SLR by 2100 and ceiling type density dependence, (b) 1m SLR by 2100 and contest type density dependence, (c) 2m SLR by 2100 and ceiling type density dependence, (d) 2m SLR by 2100 and contest type density dependence.

4.5.2 Portfolio Decision Analysis

The portfolio decision model described in the following section is composed by a multi-attribute value theory model (MAVT), a risk model, and a Pareto optimization model. MAVT and the risk model inputs are spatially explicit data and predictions of local and landscape metrics from biophysical models used in previous studies in the same area. These models are a land-cover model (SLAMM), a habitat suitability model (MaxEnt), and a metapopulation model (RAMAS) that predict respectively the land-cover change, the habitat suitability, and the species risk of species as a function of sea-level rise (Aiello-Lammens et al., 2011; Convertino et al., 2011e).

We define *restoration intervention* as any restoration that is focused on a human or natural asset in each management area. A *restoration alternative* is defined as the set of restoration interventions in each management area for all the human and natural assets that occur within it. A *management strategy* is defined as the spatial set of each restoration of an asset at the landscape scale (or equivalently defined as ecosystem scale). For example, any restoration of a species occurs locally but the decision on where to perform that restoration has implications on the whole species population. Finally, a *restoration plan* is defined as the set of restoration strategies at the landscape scale for all the human and natural assets of the ecosystem.

In the following we report some calculations and results of the portfolio decision model. Tables 11, 12, and 13 shows the MCVT models for the Snowy Plover, Piping Plover, and Military Use. The restoration actions are scored for each asset type. Figures 33 and 34 show the results of the multi-objective optimization for Santa Rosa Island (SRI). Figure 33 shows the Pareto frontiers for SRI for 2013 and 2100. Each dot in the frontier is a restoration plan for SRI. Figure 34 is an example of restoration plan in which restoration actions are specified for each management area.

Table 11. MCVT for the Snowy Plover. The value of the criteria is the same for each alternative but heterogeneous in space. The value of the criteria are defined for each management pixel. A criticality coefficient that is inversely proportional to the utility of each alternative is defined. That modifies the overall MCDA score for each alternative and the probability of success. The

restoration alternatives for the Snowy Plover are: no action, nourishment, monitoring, restoration of vegetation, restoration ephemeral pool/beach profile, predator management, and use of exclosures. The weights are assigned by expert-judgment.

Criteria			Sub-Criteria			
Name	Weight	Weight (Norm.)	Name	Maximize(1) / Minimize(0)	Weight	Weight (Norm.)
Population	3	0.600	Abundance	1	2	0.667
			Fluctuations	0	1	0.333
Habitat	2	0.400	Area	1	4	0.400
			Suitability	1	2	0.200
			Fragmentation (Df)	0	2	0.200
			Connectivity	1	2	0.200

Table 12. MCVT for the Piping Plover. The restoration alternatives for the Piping Plover are: no action, nourishment, monitoring, restoration of salt marsh, and restoration ephemeral pool/beach profile. The weights are assigned by expert-judgment.

Criteria			Sub-Criteria			
Name	Weight	Weight (Norm.)	Name	Maximize(1) / Minimize(0)	Weight	Weight (Norm.)
Population	2	0.500	Abundance	1	2	0.667
			Fluctuations	0	1	0.333
Habitat	2	0.500	Area	1	4	0.400
			Suitability	1	2	0.200
			Fragmentation (Df)	0	2	0.200
			Connectivity	1	2	0.200

Table 13. MCVT for the Military Use: The restoration alternatives for the Military Use are: no action, and nourishment. The weights are assigned by expert-judgment.

Criteria			Sub-Criteria			
Name	Weight	Weight (Norm.)	Name	Maximize(1) / Minimize(0)	Weight	Weight (Norm.)
Soldiers	2	0.667	Number	1	2	0.667
			Training Intensity	1	1	0.333
Habitat	1	0.333	Area	1	4	0.667
			Suitability	1	2	0.333

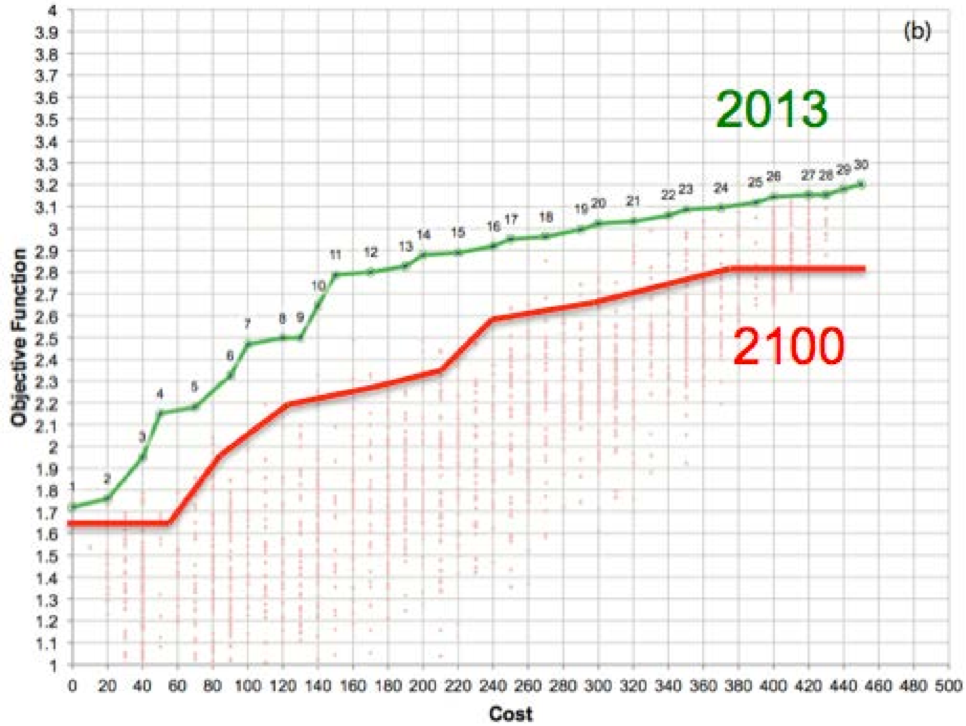


Figure 33. Pareto frontier curves obtained by maximizing the objective function (Socio-Ecological Value) unconstrained to the total cost of alternatives on the x-axis. The y-axis shows the objective function which is the socio-ecological value of a portfolio set. The curves are shown for 2013 and 2100. The red dots are unfeasible suboptimal alternatives.

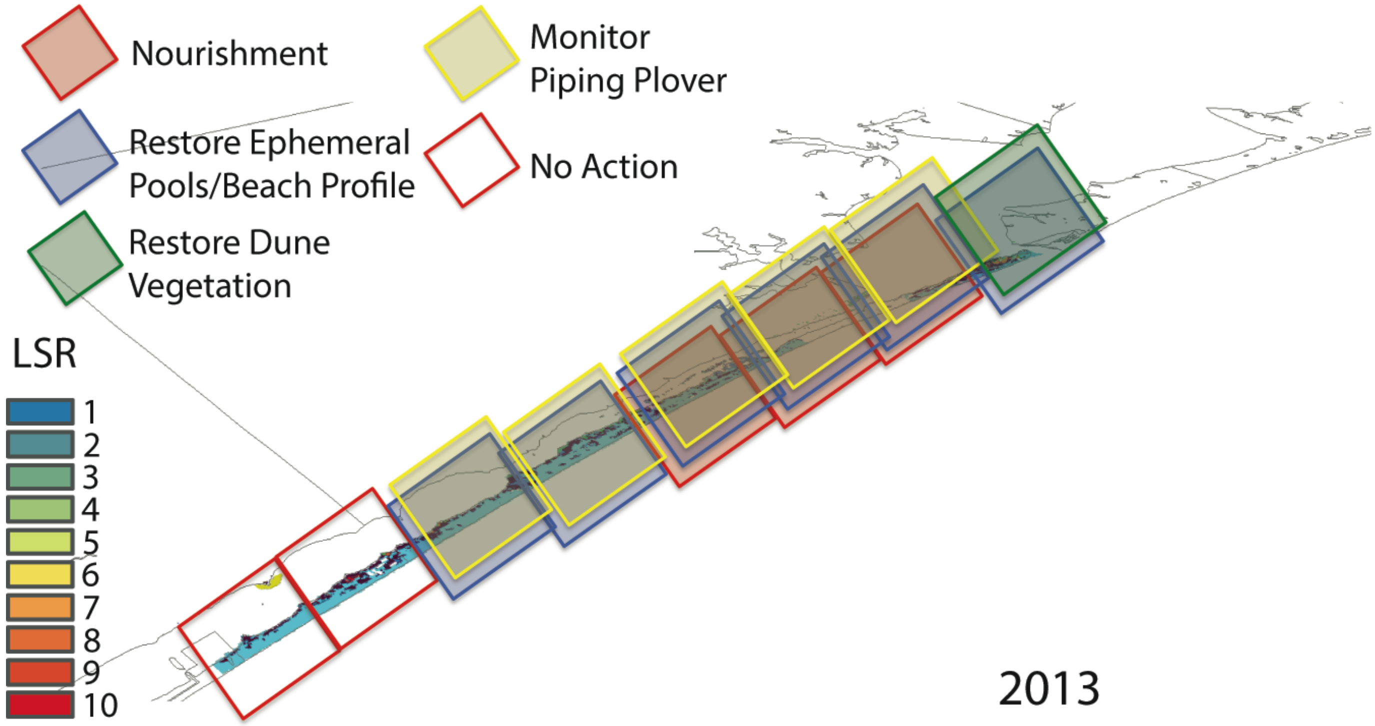


Figure 34. Example of management actions for Eglin AFB selected for the year 2013 considering the resources available equal to 300 units (i.e. "Cost'' in Figure 32). The optimal set of management actions is identified on the Pareto frontier (green curve in Figure 32). The red boxes on the map represent 600 m^2 management areas whose colors indicate different management actions. No shading, red shading, blue shading, and yellow shading within the boxes represent the management actions: no action, beach nourishment, ephemeral pool restoration, and monitor Piping Plover, respectively. Plots of management actions are available for each year of analysis and for the entire coast of Florida. The local species richness (LSR), that is the number of unique species occurring in each pixel used in the modeling with SLAMM and MaxEnt, is also shown. In this research we focused only on Snowy Plover, Piping Plover, and Red Knot.

5. Conclusions and Implications for Future Research/Implementation

5.1 Conclusions overview

5.1.1 Sea level rise simulations for Eglin AFB and the greater Florida Gulf Coast

The land cover of Eglin AFB is more stable, posting smaller habitat changes when compared to the whole Gulf Coast of Florida in the next 90 years under a SLR scenario of up to 2.0m by 2100. While these simulated results may provide temporary relief to Eglin AFB managers, the significant changes in other Florida Gulf coast habitats may cause more societal or regulatory pressure upon natural resource managers to maintain the healthy habitat within the installation boundaries as a critically important refuge.

Changes in the land cover of Eglin AFB, Santa Rosa Island, and the Eglin coast were simulated using SLAMM at different SLR projections (0.2, 0.5, 1.0, 1.5, and 2.0 m) from 2010 to 2100. Eglin AFB simulations encompass the entire range of installation lands and waters, including the barrier island system (SRI), within its jurisdiction. In order to evaluate in detail the vulnerability of the barrier island system, a separate set of simulations was carried out for SRI only. The coastline encompassing all of Eglin AFB was also assessed for vulnerability and compared with that of Tyndall AFB and the whole Gulf Coast of Florida.

Eglin AFB and SRI

The undeveloped dry land, swamps, and marshes of Eglin AFB are less likely to be affected by SLR and thus considered less vulnerable. Maximum habitat category losses were less than 0.2% (67 ha) for undeveloped area, 0.06% (68 ha) for swamps, and 0.17% (59 ha) for marsh. However, undeveloped dry land and swamp on SRI posted a much higher percent loss amounting to 8% (21 ha) and 5% (0.3 ha), respectively. Although SRI has only 0.5% of the marsh area for all of Eglin AFB, it is the most affected category by SLR. It posted a maximum loss of 18% (30 ha) during the first 30 years which is more than 50% of marsh area lost on all of Eglin AFB. The beach on SRI also incurred losses at the end of the 21th century amounting to 1.7% (24 ha) despite the fact that the beaches increased overall on all of Eglin AFB.

Eglin Coast

The land cover categories expected to manifest the highest increases in area between 2010 and 2100 at the highest SLR value of 2.0 m are tidal flat (646%) and estuarine open water (2808%). The increase in tidal flats results from the loss of swamps and marshes through erosion process, while the increase in estuarine open water results from conversion of mangrove and tidal flat. Although tidal flats showed a net increase in area, they lose some area as indicated by the increase in estuarine open water. However, these losses were compensated by the gain in area from swamps and marshes. This suggests that tidal flats will undergo wetland migration (moving inland) more often in the next 100 years than the other categories.

The most vulnerable habitat categories, posting the highest percent losses between 2010 and 2100, are regularly flooded marsh (25%), and estuarine beach (11%). In general, increasing the SLR projection will decrease the area of land cover categories. However, some categories are not affected by the different SLR projections (i.e. at SLR equal to 2.0 m, 1.5 m, 1.0 m, 0.5 m, and 0.2 m), and others may only be affected past a certain SLR value or may actually show an increase in area. Although regularly flooded marsh has one of the highest percent losses between 2010 and 2100, the effects of the different SLR projections are minimal compared to the area of the category. The beach habitat (estuarine beach, tidal flat, and ocean beach) decreased beyond

SLR = 1.0 m by 2100. The category most affected by the different SLR projections is estuarine open water which posted an increase between 2010 and 2100 of 296% at SLR = 0.2 m to 2808% at SLR = 2.0 m.

5.1.2 Florida Snowy Plover population viability under the effects of long-term sea level rise

Our linked simulations show that management options for Florida Snowy Plover under the effects of long-term SLR are possible but uncertain. Sea level rise is expected to change the geometry (temporal and spatial extent) of coastal habitat; however a solution that attempts to completely prevent these changes is unrealistic. Moreover, the global uncertainty analysis demonstrated how possible states of the coastline habitat (gains/losses) can occur. Adaptive strategies that mitigate climate change effects in the face of uncertainty (e.g. "more ecologically sustainable nourishments") seem to be the best intervention strategy for both protecting the physical habitat and the shorebirds that are strongly habitat-dependent. Specific adaptive interventions may be utilized to capitalize on coastal morphological changes with the aim to both retain positive elements and mitigate negative features within the natural variation of the environmental variables.

5.1.3 Decision analysis

The MCDA conducted here incorporated results from two models, two strategic goals, four management alternatives, and four uncertain future scenarios into a unified structure for sorting through and making sense of a variety of results within a management framework. The results of this analysis are discussed here with respect to reliability, uncertainty, and data gaps.

The MCDA investigated how the uncertainty in the sea level rise scenarios affects the alternative ranking. These results show that, using the Logical Decisions software, the alternatives rank the same between the 1 and 2 m SLR scenarios under the Coastal Protection goal. However, using JSMAA these alternatives rank differently under the 1 and 2 m sea level rise scenarios. Therefore, this work shows that a preferred alternative cannot be reliability assured under this goal given the uncertainty of future sea level rise.

The MCDA also investigated how the uncertainty in the density dependence affects the alternative ranking. These results show that, the ranking of alternatives is very different when using the contest versus the ceiling type density dependence. For example, under the Coastal Protection goal in Logical Decisions, using ceiling density dependence the rankings are (1) Exclosures, (2) Predator management, (3) Beach Nourishment, and (4) No Action. However, with contest density dependence these alternatives rank as (1) Beach Nourishment, (2) Exclosures, (3) Predator Management, and (4) No Action. Density dependence describes how a population grows relative to its population size. In ceiling density dependence, the population grows exponentially until it reaches its carrying capacity. In contest density dependence, growth is a function of the current population size and the carrying capacity. Aiello-Lammens et al. (2011) stated that current data are not sufficient to identify which type of density dependence is appropriate for Snowy Plovers in Florida. Chu-Agor et al. (2012) identified this factor as important for understanding Snowy Plover dynamics in Florida. This MCDA shows that more information on density dependence is necessary to be able to select an optimal management alternative.

Exclosures were shown to outperform Predator Management in all of the scenarios under the Coastal Protection goal. However, Exclosures did not outperform Predator Management under the Snowy Plover Protection goal. This is because of the addition of the Public Popularity measure in the Coastal Protection goal. It was assumed that Predator Management would be less

popular than Exclosures. Additionally, Colwell et al. (2008) indicated that the use of exclosures may increase the mortality of fledglings because the same predators also prey on chicks. However, due to a lack of quantitative data, in this modeling effort, the survivability of juveniles was kept constant in both the Exclosure and Predator Management alternatives. A decision between the implementation of exclosures versus predator management should involve additional work to understand the public perception of these strategies and the effects of exclosures on fledgling mortality.

The portfolio model predicts a decrease of the socio-ecological value at the ecosystem scale on average. The calculations for Santa Rosa Island recommend an increase in renourishment for decreasing the loss of beach habitat. We propose the portfolio as a tool that provides indications of restoration actions at the management scale. The biophysical models simulate restoration plans at the ecosystem scale, while the selection of the restoration actions at the management scale is performed by considering the effect of each action and their cost.

The portfolio decision analysis model performs better than the selection based on the multi-criteria decision analysis model because it diversifies restoration actions in space and time by considering their cost and benefits to the overall ecosystem. Thus, the selection of restoration actions is not performed only by selecting the dominating alternatives at one scale of analysis.

5.1.4 Structural model limitations

A model is a simplification of reality and, as such, makes generalizations and assumptions in its structure regarding how any system functions. This, along with a lack of understanding of how many parts of any system work, leads to limitations in model applicability. This does not negate the utility of model results. However, it is important to highlight these limitations to assure that a model is applied appropriately.

The SLAMM runs simulated in this effort did not account for future armoring of the beaches or other anthropogenic strategies, besides nourishment, that may be employed to protect upland development and slow sea level. Any human intervention that decreases the beach area may affect the carrying capacity and total population of the Snowy Plover. These types of strategies will likely be employed in the future, increasing the importance of ensuring that publicly owned lands preserve their beaches either through nourishment or allowing natural inland migration.

Existing and future developed lands will impact the habitat suitability of the Gulf Coast to the Snowy Plover as Snowy Plovers have been found to prefer habitats in and near undeveloped areas. In the SLAMM/MaxEnt runs, developed areas are masked out of the analysis. This strategy was taken in SLAMM to preserve the developed areas and not allow them to convert to wetlands. As a result, MaxEnt is not able to represent the proximity of development as a criteria for habitat suitability. In reality, Snowy Plovers prefer to nest on beaches that are not adjacent to developed lands. Additionally, in SLAMM all existing infrastructure areas are maintained at current levels because the future of development is unknown. These limitations of accounting for developed area should be considered when applying conclusions from this work to areas that are near or in developed areas.

The effect of how nourishment affects Snowy Plovers remains unclear. It is likely that there is not a direct relationship between habitat availability and plover population size. Assumptions and limitations of how nourishment affects Snowy Plovers can be found in Convertino et al. (2011), Weber (2011), and Lott (2009). For example, a negative correlation was found by Lott (2009) between beach nourishment and Snowy Plover populations. However, Weber (2011) investigated this notion and found that high human use and high vegetation

density were the main factors that discouraged snowy plover site selection. Amount of debris on a beach and access to the bay side of barrier islands, positively affected the probability of occupancy, mainly during the nesting stage. Coastal engineering projects, that stabilized primary dunes (e.g., dune restoration and vegetation planting), promoted denser vegetation, which discouraged snowy plover occupancy throughout the breeding season. Beach nourishment projects were less likely to influence beach characteristics that contribute to plover habitat selection. Additionally, nourishment can have detrimental effects on food-web structures (Menn, 2002a, b; Greene, 2002; Guilfoyle et al., 2006; de la Huz and Lastra, 2008). Nourishment plans should take into consideration species ecological and habitat requirements such as the timing of a nourishment project, grain size and sorting, and the microhabitats designed within the nourishment project.

The quality of the input data imposes limitations on the reliability of model results. Chu-Agor et al.'s (2011) results also showed that, in the SLAMM model, four input factors (DEM vertical error for the lower elevation range, historic trend of sea level rise, accretion, and sedimentation rates) controlled 88-91% of SLAMM's output variance in predicting changes in the beach habitat of Eglin Air Force Base, and Aiello-Lammens et al. (2011) found that the RAMAS model is most sensitive to survival rate and fecundity. Therefore, the quality of the model results will largely depend on the accuracy of these most important input factors.

5.2 Summary

This work presents a linked model process to simulate the fate of shorebird TER-S populations as impacted by sea level rise. A land cover model (SLAMM) is linked with a habitat suitability model (MaxEnt), which is in turn linked to a demographic model (RAMAS). The models explore how sea level rise and habitat migration affect the ability of these TER-S to breed, successfully raise young, and to find an adequate forage base. Uncertainty is considered in model predictions as well as in sea level rise scenarios. Decision analysis techniques, including MCDA and portfolio analysis are applied to aid management decisions in the face of this complex and uncertain problem. Land cover changes as a result of sea level rise are simulated at Eglin and Tyndall AFB as well as throughout Florida's Gulf Coast. The benefits of this research are: (1) the integration of models that are generally applicable to any coastal ecosystems; (2) the quantification of the drivers and uncertainty of ecogeomorphological processes; and (3) the formulation of environmental management recommendations for the sustainability of the Florida coastal ecosystems.

This research also highlighted areas for future research. Additional work in model development and parameterization would improve model results. For example, including hydrodynamics and sediment transport processes in the SLAMM model would improve the physical representation of habitat migration due to sea level rise. The sensitivity analysis also highlighted the importance of aggradation in determining habitat migration. Better data on this process for wetlands would improve model results and decrease model uncertainty. Also, a better understanding of shorebird life histories, particularly the type of density dependent reproductive strategies employed, would decrease model uncertainty and improve model results. The literature is clear that Snowy Plovers prefer unpopulated areas; however MaxEnt was unable to consider this factor. Simulating, this aspect of Snowy Plover dynamics would also improve model results an aid in determining the best management tools for specific areas.

The work presented here shows that Snowy Plover populations will decrease faster than the rate of habitat loss. It is therefore, important to work toward species conservation now before major losses to habitat occur. The MCDA showed that a no action approach to Snowy Plover

conservation is generally the least desirable management strategy. Additionally, nourishment and exclosure practices were shown to be the most desirable management strategies. Nourishment schemes need to take into account the needs and vulnerabilities of TER-S such as timing and the design of micro-habitats. These conclusions give managers specific preferred alternatives for preserving shorebird TER-S in the face of sea level rise and habitat loss. The portfolio decision analysis model considers the local needs of stakeholders and environmental heterogeneities by running the restoration actions at the global scale as well as evaluating benefits and costs of each action at the local scale.

We show that a decision analytical model that groups data, predictions of environmental models, costs, and stakeholder preferences should be formulated for developing indications of restoration actions.

This study shows the importance of an integrated science-based analysis of environmental patterns and processes as a function of climate change. However, the understanding of the local and global effects of climatic stressors on the ecosystem should not be the endpoint of the analysis.

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Appendices

B. List of Scientific/Technical Publications:

B1. Articles in peer-reviewed journals

Aiello-Lammens, M.E., Chu-Agor, M. L., Convertino, M., Fischer, R., Linkov, I., and Akçakaya, H.R. 2011. The impact of sea-level rise on Snowy Plovers in Florida: Integrating geomorphological, habitat, and metapopulation models. Global Change Biology 17(12): 3644-3654.

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Convertino, M. K. Baker, R.A. J. Keisler, G. Kiker, C. Foran, I. Linkov (2012). Spatially-explicit Portfolio Decision Model for Optimal Multispecies Management and Integration of Ecological Models, *Ecological Applications, in submission.*

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B2. Technical reports

I. Linkov, R.A. Fischer, M. Convertino, M. Chu-Agor, G. Kiker, C.J. Martinez, R. Muñoz-Carpena, H.R. Akcakaya, and M. Aiello-Lammens, (2010). The Proof of Sea-level Rise is in the Plover - Climate Change and Shorebirds in Florida, *Endangered Species Bullettin (US FWS)*

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B3. Conference or symposium proceedings scientifically recognized and referenced

Kiker, G., Convertino, M, Chu-Agor, M.L., Aiello-Lammens, M., Kiker, G.A., Muñoz-Carpena, R, Ak- cakaya, H.R., Fischer, R.A., and Linkov, I., Integrated Modeling for Risk Assessment of Shoreline- dependent Species Threatened by Sea-level Rise, Society of Risk Analysis Annual Meeting, Charleston, SC, December 2011, and SERDP-ESTC meeting, Arlington, VA, November 2011

M. Convertino, J.F. Donoghue, M.L. Chu-Agor, G.A. Kiker, R. Muñoz-Carpena, R.A. Fischer, I. Linkov, Anthropogenic Renourishment Feedback on Shorebirds: a Multispecies Bayesian Perspective for Beach restoration in the face of Climate Change, National Conference on Ecosystem Restoration (NCER), Baltimore, August 2011

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M. Aiello-Lammens, H.R. Akcakaya, Convertino, M., Fischer, R., Kiker, G., Martinez, C., and Linkov, I., Integrated Climate Change and Threatened Bird Population Modeling to Assess Risks from Changes in Sea-level and Weather Patterns, 24th International Congress for Conservation Biology (ICCB 2010), Edmonton, Alberta, Canada, 3-7 July 2010

B4. Conference or symposium abstracts

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B5. Text books or book chapters

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